Effect of nonradiative recombination on light emitting properties of two-dimensional photonic crystal slab structures

Han-Youl Ryu, Jeong-Ki Hwang, Dae-Sung Song, Il-Young Han, and Yong-Hee Lee
Department of Physics, Korea Advanced Institute of Science and Technology, Taejon 305-701, Korea

Dong-Hoon Jang
Telecommunication Basic Research Laboratory, Electronics and Telecommunications Research Institute, Taejon 305-600, Korea

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InGaAsP-based two-dimensional photonic crystal light emitting structures are fabricated by employing wafer fusion and characterized optically. The structure does not contain defect regions and the whole area of the photonic crystal is used for light generation and extraction. The effect of nonradiative recombination is studied as a function of pump power. The relative contribution of surface recombination can be as low as 10% as pump power increases since carrier recombination is dominated by Auger recombination. In spite of the large surface-to-volume ratio of the photonic crystal pattern, over four-fold enhancement of photoluminescence extraction efficiency is observed.


Photonic crystals enable one to control the optical emission properties of materials placed inside them. They can, for example, modify the spatial distribution of radiation power, change the spectral width of the emitted light, and enhance or suppress the spontaneous emission rate. Recently, a two-dimensional (2D) photonic crystal structure combined with an optically thin dielectric slab has attracted much attention. High light-extraction efficiency is expected in this structure, which leads the photonic crystal slab to the potential application to a high-efficiency light emitting diode (LED).

However, the problem of surface recombination in this structure having large surface-to-volume ratio still remains to be addressed. Recently, Boroditsky et al. demonstrated the enhanced light extraction from photonic crystal slab structures made by epoxy bonding. However, due to large surface recombination effects, they proposed a photonic crystal LED structure in which light generation region was separated from the photonic-crystal light extraction region. Baba et al. mentioned the large contribution of surface recombination in a two-dimensional photonic crystal made of microcolumns. In this letter, we present characteristics of InGaAsP-based air-hole photonic crystal light emitting structures made by wafer fusion and wet oxidation and the analyses of surface recombination effects on the radiative properties. This structure does not contain defect regions for light generation. Therefore, the whole area of the photonic crystal can be used for both light generation and light extraction. It will be shown that surface recombination of periodic photonic crystal structures could not be a significant problem in the long-wavelength LED application in spite of the large surface-to-volume ratio.

Our photonic crystal slab is schematically shown in Fig. 1. Six compressively strained (0.6%) InGaAsP quantum wells are used as an active material for preferred coupling to TE-like modes which have electric field components almost parallel to the slab. One side of the InGaAsP/InP guiding layer is bonded to the AlAs layer on top of GaAs substrate by the wafer fusion technique. This wafer-fusion step is employed to realize a thermally stable and mechanically robust device. After electron-beam lithography and chemically assisted ion-beam etching using Ar/Cl₂, the AlAs layer is converted to low-index Al oxide by wet oxidation processes to achieve optical confinement in the vertical direction. The thermal conductivity of Al oxide is much higher than air or glass, so good thermal property is expected in this slab structure. Since the air-hole pattern is deeply transferred through the oxide bottom cladding layer, mode profiles inside the slab is nearly symmetric and the refractive index contrast is reasonably large. The resulting pattern is a triangular array of air holes. Total thickness of the InGaAsP/InP guiding layer is 320 nm. Lattice constant is varied from 280 to 910 nm while maintaining the ratio of a hole radius to lattice constant of about 0.24.

The fabricated photonic crystal slab structures are optically pumped by a 980 nm laser diode with 10% duty cycle to reduce thermal effects. The pump spot size is about 5 μm and the total size of a photonic crystal pattern is 20 μm. Photoluminescence (PL) is collected from the top of a sample using a microscope objective with a numerical aperture of 0.4. The PL spectra for two patterned samples along with an unpatterned sample are shown in Fig. 2(a) when the peak pump power in front of the sample is 10 mW. The
modes can couple into air. Dark areas indicate the emission region. Dashed lines represent the light lines above which optical methods are not supported.

Top, middle, and bottom areas correspond to the regions for lattice constant of 910, 640, and 460 nm, respectively. Each peak in the spectra of Fig. 2(a) corresponds to a leaky conduction band mode near the \( \Gamma \) point of the Brillouin zone. For the 640 nm sample, these peaks are well resolved as shown in Fig. 2(a). This resonance phenomenon is similar to those reported in other literatures.\(^7\)\(^12\) In general, the total PL intensity increases with lattice constant as shown in Fig. 2(b). The increase of the relative PL enhancement with lattice constant is attributed to the increase of the density of leaky modes. For example, as shown in Fig. 3, nearly all the modes are leaky for the 910 nm sample in contrast to the 460 nm sample where the majority of the mode is confined inside the photonic crystal slab waveguide. Surface recombination effect is also partly responsible for the behavior of Fig. 2(b) because the average relative distance to the nearest surfaces increases with lattice constant.

The external conversion efficiency of a LED is given by

\[
\eta = \eta_i \cdot \eta_r \cdot \eta_e \cdot \eta_a, \quad \text{where } \eta_i, \eta_r, \eta_e, \text{ and } \eta_a, \text{ respectively, are injection, radiative, extraction, and Auger recombination coefficients.} \]

\[
\eta_r = \frac{BN^2}{AN + BN^2 + CN^3},
\]

where \( N \) is carrier density.\(^11\) \( A \) is the surface recombination coefficient which is given by the multiplication of surface-to-volume ratio and surface recombination velocity, \( \nu_s \). For triangular lattice of air holes, \( A \) is expressed as

\[
A = 4 \pi \nu_s / (3a^2f),
\]

where \( r, a, \text{ and } f \) are the air-hole radius, lattice constant, and the filling ratio of active region, respectively. \( B \) and \( C \) are the bimolecular recombination and the Auger recombination coefficient, respectively. The Auger recombination has often been neglected in the analysis of the surface recombination effect in photonic crystals.\(^7\)\(^8\) However, it should also be taken into account especially for small band gap semiconductors. Other nonradiative process related to defects and impurities are assumed to be negligible.

The radiative efficiency is plotted as a function of carrier density for three values of surface recombination velocities in Fig. 4, \( B \) (1.0 \( \times \) 10\(^{-10}\) cm\(^3\)/s) and \( C \) (3.0 \( \times \) 10\(^{-29}\) cm\(^3\)/s) of InGaAsP are used for our calculation.\(^11\) At low carrier density, the radiative efficiency of a photonic crystal is limited...
mainly by surface recombination. However, Auger recombination becomes dominant at high carrier density of over $3.0 \times 10^{10}$ cm$^{-3}$. As the surface recombination velocity decreases, the relative contribution of surface recombination becomes small at this carrier density. Since Auger recombination is common to patterned and unpatterned samples, radiative efficiencies for these two cases are similar at high carrier density.

In order to justify the above argument, the PL of photonic crystal structures is measured as a function of incident pump power, $P$. For three samples of different lattice constants, the relative enhancement $R$ vs $P$ is plotted as solid dots in Fig. 5 along with fitted curves. At steady state, the carrier density is

$$N = \sqrt{\frac{\eta_0 \alpha P}{VBhv}}$$

where $\alpha$ is the fraction of absorbed pump power, $V$ is the active volume, and $v$ is the frequency of the pump source. The enhancement factor $E$ defined in Eq. (1) is used as a fitting parameter. By numerically solving Eq. (1) with Eqs. (2) and (3), the enhancement factor is determined using $v_s$ of 1.0 $\times$ 10$^4$ cm/s and $\alpha$ of 0.11.\textsuperscript{13} For the samples of lattice constants larger than 640 nm, the enhancement factor is found to be 10\%-15\% larger than the measured relative PL enhancement at 10 mW. Remembering that by definition $E$ equals $R$ when the surface recombination effect in photonic crystal LEDs are eliminated, the contribution of the surface recombination is believed to be about 10\%-15\% with 10 mW pumping onto a 5 $\mu$m spot. In this case, the carrier density is about $5 \times 10^{18}$ cm$^{-3}$ which is well within the range of a practical operation.\textsuperscript{14} At low pump power, the relative PL enhancement $R$ is small but increases rapidly. In this regime, $R$ and $\eta_0$ is limited by the surface recombination. At high pump power, $P > 5$ mW, the relative PL enhancement increases very slowly and begins to saturate. In this regime, the surface recombination becomes less important compared to radiative and Auger recombination. These results are consistent with the calculation previously shown in Fig. 4.

In summary, photonic crystal slab light emitting structures are fabricated and characterized by optical pumping. Over four-fold enhancement of the PL relative to the unpatterned region is observed. It is found that, under a high pumping condition, the relative contribution of surface recombination can be as low as 10\%, and the effect of the surface recombination in the photonic crystal is not as severe as one expected because the Auger recombination becomes dominant at high carrier density. In addition, since our photonic crystal slab structure does not have light generating defect regions inside, large area LEDs could be easily fabricated. This photonic crystal structure can be a promising candidate for efficient LEDs.

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\textsuperscript{1}E. Yablonovich, Phys. Rev. Lett. 58, 2059 (1987).
\textsuperscript{13}It is found that small variation of material constants, $v_s$, $B$, $C$, or $\alpha$, does not affect the fitting results appreciably.