Directional light extraction from thin-film resonant cavity light-emitting diodes with a photonic crystal

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We report directional light extraction from AlGaInP thin-film resonant cavity light emitting diodes (RCLEDs) with shallow photonic crystals (PhCs). Diffraction of guided modes into the light extraction cone enhances the light extraction by a factor of 2.6 compared to unstructured RCLEDs, where the farfields still show higher directionality than Lambertian emitters. The external quantum efficiency is 15.5% to air and 26% with encapsulation, respectively. The PhC-RCLEDs are also more stable to a temperature induced wavelength shift than unstructured RCLEDs. © *2008 American Institute of Physics*. [DOI: 10.1063/1.3046130]

The efficiency of red AlGaInP light-emitting diodes (LEDs) is limited by poor light extraction caused by the high refractive index contrast between AlGaInP and air. In the past decade, several methods have been developed to increase the external quantum efficiency from below 3% for AlGaInP LEDs on an absorbing GaAs substrate to above 50% for emission at 650 nm.[1,2] One of the successful solutions is the thin-film LED, where epitaxial layers are mounted on a carrier wafer with an intermediate metal mirror and contact. The subsequent removal of the absorbing substrate results in a thick cavity with losses only in the active region and at the contacts. The light extraction efficiency can be improved significantly by incorporating buried microreflectors and random surface texturing.[2] The latter measure results in a Lambertian farfield emission pattern where the directionality is $D(\theta)=(\sin\theta)^2$. The directionality is defined as

$$D(\theta) = P(\theta)/P(90°) = \int_0^{\theta} I(\theta')\sin\theta' d\theta' \Big/ \int_0^{90} I(\theta')\sin\theta' d\theta', \qquad (1)$$

where $I(\theta')$ is the measured intensity at the angle θ'. While this yields high overall extraction efficiency, a more directional emission profile is desirable for many applications as it increases the coupling efficiency to an external optical system with a limited numerical aperture. Such directional emission can be achieved with resonant cavity LEDs[3–5] (RCLEDs) first proposed by Schubert *et al.*[6] and have been investigated thoroughly theoretically.[7–9] However, the higher directionality in AlGaInP RCLEDs has been obtained with an external quantum efficiency of only 23% in encapsulation at its best.[3] Furthermore, the efficiency dependence on temperature is worse for resonant cavity based devices, since the emission spectrum and the cavity detune as the temperature increases.[4] Photonic crystals (PhCs) have been applied to LEDs with the purpose of diffracting guided light into the light extraction cone by a number of authors,[10–16] and it has been shown that the directionality of the emitted light for GaN LEDs can be enhanced.[17] Recent work on PhCs applied to a AlGaInP thin-film LED did indeed show that the extraction efficiency can be enhanced by almost 50% compared with a flat surface by extracting high order modes with an effective index $n_{eff} < n_{PhC}$, where n_{PhC} is the effective refractive index of the PhC.[16] However, the large number of guided modes in the thick (>4 μm) epitaxial film left little room for a directionality enhancement of the farfield.

In this letter, we show that the light extraction from AlGaInP RCLEDs can be greatly enhanced by using a thinner epitaxial film and applying a shallow PhC, while maintaining a super-Lambertian emission pattern and at the same time improving the temperature stability. This reduction in layer thickness can be achieved without loss of carrier injection uniformity because we introduce a transparent conductive oxide (TCO) layer that acts as the current spreading layer. The total thickness of the epitaxial layers is 1.4 μm, which results in fewer modes with higher intensity. Furthermore, the formation of a $5\lambda/2$ cavity between the bottom metal mirror and the top distributed Bragg reflector (DBR) enhances the light extraction efficiency and provides higher directionality of the directly emitted light. The DBR impact on the guided mode distribution on the other hand is negligible. Our approach is analog to the grating-assisted RCLED treated in Ref. 18, but with the major difference that the PhC is placed on top of the cavity and not within it. In this way, the Fabry–Pérot (FP) resonance is less sensitive to deviations of the PhC etch depth and air filling factor.

The PhC diffracts guided modes with in-plane wave vector $\vec{k}_i = |\vec{n}_{eff,i}| k_0$ $(1 < |\vec{n}_{eff,i}| < n_{QW})$ according to Bragg's law,

$$\vec{n}_{eff,d}(k_x,k_y) = \vec{n}_{eff,i}(k_x,k_y) + \vec{G}/k_0. \qquad (2)$$

Since extraction to air requires that $|\vec{n}_{eff,d}| < 1$, the allowed mismatch between a reciprocal lattice vector $\vec{G}$ and the effective index of the incident guided mode is $\Delta = |\vec{n}_{eff,i} - \vec{G}/k_0| < 1$, where k_0 is the vacuum wave number. Hence, the PhC extracts only a limited range of the guided modes expressed in terms of effective index $n_{eff} = |\vec{n}_{eff}|$. More generally, the allowed mismatch for extraction within a limited external extraction angle θ_{ext} requires that $\Delta = |\vec{n}_{eff,i} - \vec{G}/k_0| < \sin\theta_{ext}$. We choose lattice constants a in the range 310–500 nm, corresponding to $G/k_0 = 1.5$–2.4, in order to diffract

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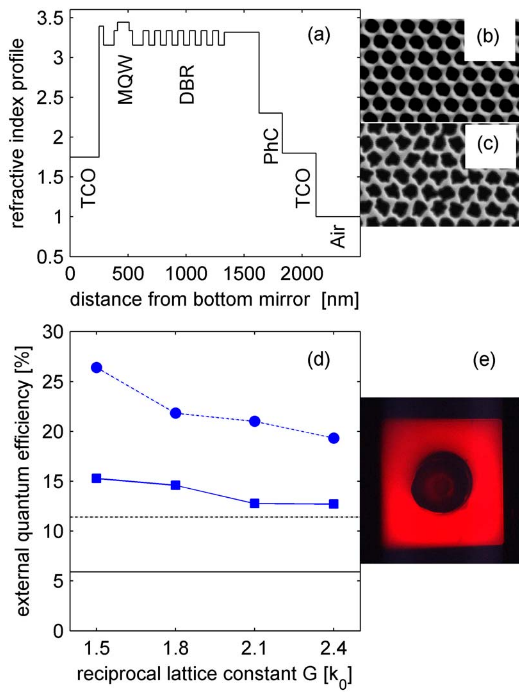

FIG. 1. (Color online) (a) Refractive index profile of the PhC-RCLED. Scanning electron microscope image of the PhC on an (b) etch test sample and on the (c) characterized sample. External quantum efficiency at 30 mA as a function of the reciprocal lattice constant of the PhC for extraction to air (squares) and for encapsulated chips (circles). (d) Efficiency for unstructured RCLEDs plotted as horizontal lines (solid line to air and dotted line for encapsulation). (e) Microscope image of PhC-RCLED under operation.

high order modes with a high overlap with the PhC.

The RCLEDs were grown by metal-organic vapor phase epitaxy on a GaAs substrate. The vertical refractive index structure of the processed RCLEDs can be seen in Fig. 1(a). It has a combined TCO/Au mirror and *p*-contact. The active region consists of five GaInP quantum wells emitting at 650 nm with $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ barriers embedded between 90 nm thick AlInP electrical confinement layers. The DBR consists of seven pairs of $\lambda/4n$ thick $(Al_{0.95}Ga_{0.05})_{0.5}In_{0.5}P$ and $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ layers. The refractive index contrast between the two DBR material components is only $\Delta n=0.16$, which results in a calculated reflectivity of 35% with a full width at half maximum (FWHM) of 36 nm. The hexagonal PhCs were defined on 400 nm thick ZEP520A resist by e-beam lithography and subsequently etched via a hard mask with chlorine-based inductively coupled plasma to a depth of 200 nm. After removal of the hard mask, the PhC was covered with 290 nm TCO that connects the whole chip with 210 μm side length to the central bondpad. The hole shape of the fabricated PhCs on the characterized devices was irregular since the hard mask eroded during etching [see Figs. 1(b) and 1(c)]. The simulated extraction efficiency η_{extr} with the method is given in Ref. 19 for a RCLED without a PhC is 6.6% to air when emission from all quantum well positions and the spectral width of the internal emission is taken into account. However, the redistribution of light from guided modes to radiating modes through photon recycling is not included in Ref. 19. For devices with high internal efficiency, this effect can cause an extraction efficiency enhancement of several hundreds of percent.[16,20]

The efficiency of the PhC-RCLEDs was measured in an integrating sphere and is plotted as a function of the reciprocal lattice constant of the PhC in Fig. 1(d). The highest external quantum efficiency η_{QE} is 15.5% for PhC-RCLEDs mounted on TO18 headers and 26% for encapsulated PhC-RCLEDs. The latter efficiency is higher than the highest reported efficiency of unstructured AlGaInP RCLEDs. The corresponding values for the unstructured reference RCLEDs is 5.9% and 11.6%. A comparison between the experimental η_{QE} and the simulated extraction efficiency η_{extr}, where $\eta_{QE}=\eta_{int}\eta_{extr}$, shows that the internal efficiency η_{int} is well below 90%, which indicates that photon recycling does not contribute substantially to the external efficiency. The highest quantum efficiency η_{QE} is obtained between 20 and 30 mA, corresponding to 63–95 A/cm^2. This remarkably high current density for which η_{QE} reaches its maximum is a further indicator of high nonradiative recombination, as nonradiative effects have most impact at low current densities. On the other hand, excellent current distribution over the whole chip area via the TCO contacts as seen in Fig. 1(e) ensures the lowest possible local current density, which minimizes current leakage over the thin confinement layers at high currents. The PhC enhancement factor for extraction to air measured at 30 mA is in the range of 2.2–2.6, with highest extraction efficiency for the smallest reciprocal lattice constant $G=1.5k_0$ ($a=500$ nm). It is worth noting that this dependency on G is similar to the results in Ref. 16. To determine the directionality of the emitted light, spectral farfields were measured with an optical fiber mounted on a rotating arm (step size 1°) connected to a spectrometer and they are shown in Figs. 2(a) and 2(b). The farfields are normalized with the integrated emission spectrum and a Lambertian emission profile. The $5\lambda/2$ cavity is thin enough to allow for only one FP resonance in the farfield within the spectral width as seen in Fig. 2(a) for the unstructured RCLED. The directionality $D(30°)=31\%\pm1\%$ of the emitted light is considerably better than for a Lambertian emitter, which has $D(30°)=(\sin 30°)^2=25\%$.

We now turn to the temperature dependence of the unstructured and structured emitters, respectively. The right-

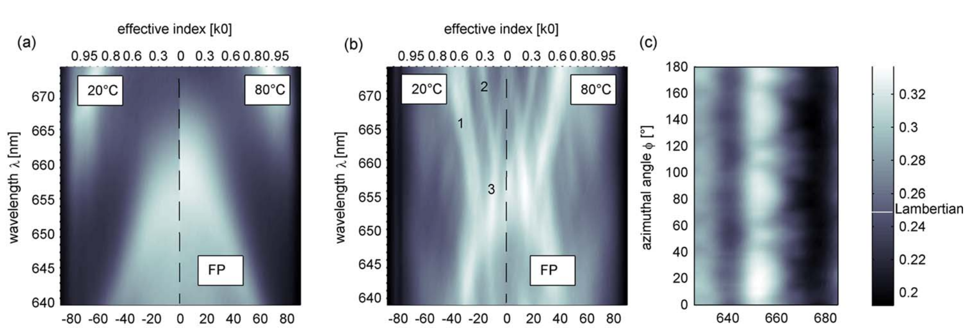

FIG. 2. (Color online) Normalized spectral farfield for an (a) unstructured RCLED and for a (b) PhC-RCLED with $G=1.5k_0$ measured at 20 °C (left side) and 80 °C (right side). Three strong diffraction lines can be seen together with the boomerang-shaped FP mode for the PhC-RCLED. (c) Directionality D (30°) as a function of emission wavelength and azimuthal angle for the same PhC-RCLED.

hand side of Fig. 2(a) shows the farfield measured at 80 °C for the unstructured emitter. The redshift of the spectrum is 7 nm and the FWHM is increased from 18 to 23 nm. The emitted flux drops by 30%±1.1% between 20 °C, and 80 °C, which is due to the thermal wavelength detuning from the FP resonance and a drop in internal efficiency. Simulations suggest that the extraction efficiency drop is 20% and the internal efficiency drop contributes 10% to this figure. In comparison, the farfield for the PhC-RCLEDs is slightly less directional than the bare RCLEDs, but varies less with temperature; the most efficient PhC-RCLED with $G=1.5k_0$ has also the highest directionality with 29%±1% in a 30° cone. The farfield in the ΓM-direction measured at 20 °C is seen on the left-hand side in Fig. 2(b). The boomerang-shaped FP-mode can still be recognized. Three additional diffraction lines labeled 1–3 in Fig. 2(b) apparently contribute to the light extraction. The effective index of the corresponding modes is 1.19, 1.47, and 1.74 for $\lambda=650$ nm from Eq. (2). The right hand side of Fig. 2(b) then shows the farfield of the PhC-RCLED at 80 °C. The diffraction lines are almost identical for the two different temperatures and the temperature induced emission drop is reduced to 27%±1.5%. Assuming that the internal efficiency drop is similar to the bare RCLED, we calculate the extraction efficiency drop to be 17%. This improved temperature stability of the PhC-RCLED is explained by the reduced light extraction dependency on the FP-resonance; instead, the extraction is dominated by the PhC extraction channels that have weaker temperature dependence.

Finally, we assess the impact of the hexagonal nature of the lattice on the directionality. Figure 2(c) shows the fraction of the emitted light within a ±30° cone as a function of the azimuthal angle Φ (azimuthal step size 3°) and the wavelength λ of the PhC-RCLED. The directionality depends most strongly on λ with a maximum close to the peak wavelength. The strong λ-dependence is mainly caused by the FP resonance as seen in Fig. 2(b) but also because the strongest diffracted mode [mode 1 in Fig. 2(b)] falls outside the 30° cone for $\lambda>660$ nm. The extraction of this mode would have been more directional with a smaller reciprocal lattice constant. A 60° periodicity is seen in the directionality dependence on the azimuthal angle Φ as expected from a hexagonal lattice. However, the azimuthal contrast $[P(30°)]^{max}-P[(30°)^{min}]/[P(30°)]^{max}+P[(30°)^{min}]<7\%$ within the FWHM of the emission spectrum is quite small. Although such in-plane nonuniformity may be unwanted for some applications, we conclude that it is of minor importance for the directionality.

In summary we fabricated thin AlGaInP thin-film PhC-RCLEDs emitting at 650 nm. The measured external quantum efficiency up to 26% at high current density exceeds previous records for AlGaInP RCLEDs without PhCs. Analysis of spectral farfields shows that PhCs can enhance the extraction efficiency from resonant-cavity LEDs by 160% while still maintaining higher directionality than Lambertian emitters. It is also noteworthy that the quality of the etched lattice, which is relatively poor as seen in Fig. 1(c), has little impact on the extraction efficiency, as the relevant modes can be clearly distinguished.

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