Enhanced Extraction from a Light-Emitting Diode Modified by a Photonic Crystal and Lasing Action

Personnel

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Semiconductor LEDs have the potential to be low-cost and long lifetime solid-state lighting sources for applications as varied as room lighting and flat-panel displays. LEDs are also used in short-range telecommunication systems and may be desirable for optical interconnects in computers. Unfortunately, most of the light emitted from a semiconductor LED is lost due to total internal reflection resulting in low extraction efficiency.

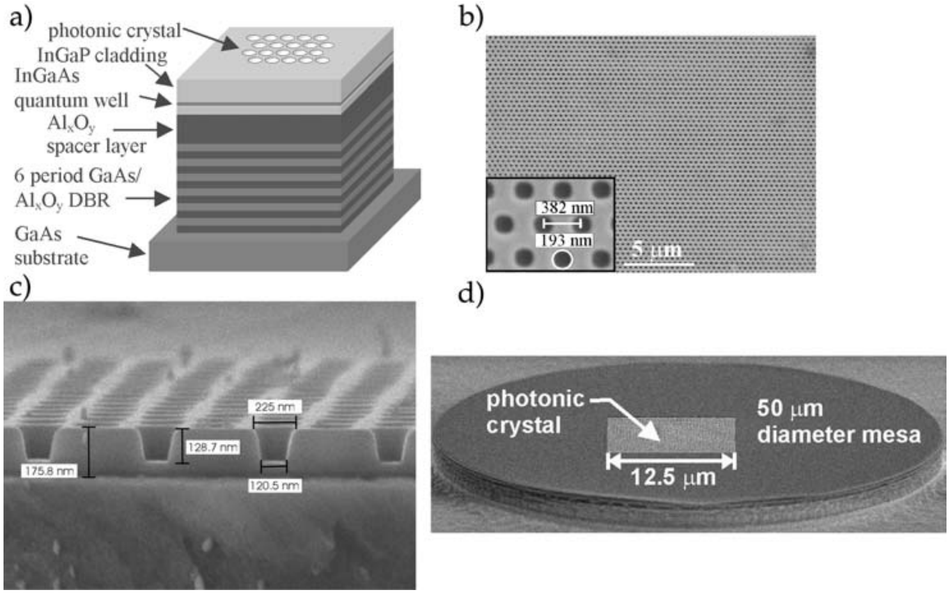

Fig. 4: a) A schematic of the 2D PC structure. b) Plan view of the photonic crystal structure. c) Cross section view of the photonic crystal. d) A completed device.

In this work, the effect of a two-dimensional (2D) Photonic Crystal (PC) on the emission properties of a Quantum Well (QW) inside a LED is examined. Enhanced extraction of light into the vertical direction is obtained and attributed to the presence of leaky resonant states created by the coherent scattering from the periodicity of the PC. The 2D PC is fabricated in the top cladding layer of an asymmetric active region that emits at _ = 980 nm with a full-width at half-maximum of approximately 60 nm at room temperature. The photoluminescence (PL) emission at 935 nm, normal to the surface, is enhanced by a factor of 100 and the spectrally integrated PL is enhanced by a factor of 8, both when compared to a reference structure without a PC. When optically pumped above threshold, lasing occurs at a wavelength of 1005 nm. This work provides a basis for the design of high efficiency LEDs and lasers based on 2D PCs.

The 2D PC consisting of a triangular lattice of holes etched within the upper InGaP cladding layer of a mesa is shown schematically in Figure 4(a). To minimize carrier recombination at the etched surfaces, the holes do not penetrate the InGaAs QW; however, the hole depth is sufficient to cause enhanced extraction of light and laser feedback. The device structure is grown using gas-source molecular beam epitaxy. The separation layer is initially grown as $Al_{0.98}Ga_{0.02}As$ and the distributed bragg reflector (DBR) consists of AlAs and

GaAs layers. A SiO_2 layer is deposited on the grown structure using electron beam evaporation within the NanoStructures Laboratory (NSL). The holes are defined in PolyMethyl MethAcrylate (PMMA) by direct-write electron-beam lithography. The electron beam writes a square pattern in the PMMA to represent each hole. The beam size, however, is larger than the step size used to translate the electron beam, which leads to the desired circular pattern following development.

The PMMA is used as a mask in transferring the triangular pattern into the SiO_2 layer using the NSL Reactive Ion Etcher (RIE). This is accomplished with a CHF_3 plasma using 15 second etches in between one minute cool-down steps. The purpose of the cool-down step is to prevent the flowing of the PMMA mask. The SiO_2 mask is subsequently used in the RIE of the holes into the upper InGaP cladding layer using a $CH_4/H_2/O_2$ plasma in an 8:8:1 gas flow ratio. The mesas are next defined using photolithography followed by RIE with the $CH_4/H_2/O_2$ plasma to etch the active region and a BCl_3 plasma to expose the mesa sidewalls. The final step in the device fabrication is the wet thermal oxidation of the $Al_{0.98}Ga_{0.02}As$ separation layer and the AlAs DBR layers. Figure 1(b) shows a PC structure with lattice constant of 382 nm, hole diameter of 193 nm, hole depth of 101 nm, and an active region thickness of 198 nm that was imaged using a Scanning Electron Microscope (SEM); this structure is characterized and the results are reported below. Figure 1(c) shows a cross sectional view of a photonic crystal while Figure 1(d) shows a completed device.

The PhotoLuminescence (PL) is observed using a cw $Ti:Al_2O_3$ laser with an emission wavelength of 785 nm. Figure 2(a) shows a spectrum of the enhancement of PL from the PC region normalized to the same structure but without a PC. Figure 5(b) is a calculation of the photonic band structure near the Γ point in the first brillouin zone. The bands represent leaky resonant states that provide a pathway for the enhancement of light extraction. On the long wavelength end of the spectrum, the range covered by the first three bands closely matches the large observed peak centered near 935 nm. The width of the peak is determined by the quality factor of the leaky resonance and by the collection angle (dotted line). Band 4 and bands 5 and 6 closely match the peaks near 890 nm and 860 nm, respectively. The dip between peaks 2 and 3 corresponds to the gap in available states between bands 3 and 4.

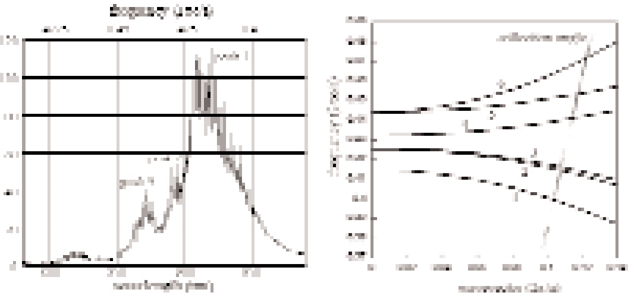

Fig. 5: a)Photoluminescence enhancement spectrum from PC structure. b) Calculated photonic band structure near Γ point

Scattering along the high-symmetry directions within the photonic crystal also provides sufficient distributed feedback for lasing to occur. Figure 6(a) shows the emission spectra from a photonic crystal optically pumped just above threshold. The lasing peak, which occurs at a wavelength of 1005 nm, corresponds with the bending of bands at the M point Figure 6(b).

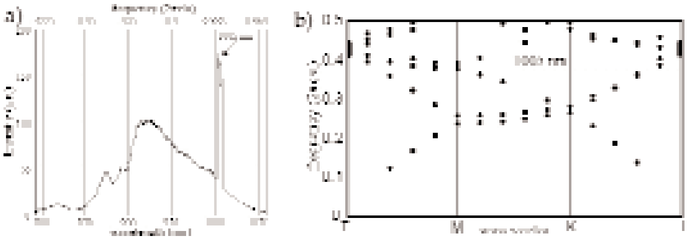

Fig. 6: a) Lasing spectrum. b) Calculated band structure showing band folding near M point.