Enhanced light extraction from circular Bragg grating coupled microcavities

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A 7-fold enhancement of light extraction from a vertical-cavity light-emitting diode structure over a 130 nm bandwidth at room temperature was achieved using circular Bragg gratings. The enhancement factor corresponded to a 41% external efficiency.

The development of nanophotonic structures such as photonic crystals to enhance light extraction[1–4] could offer superior efficiency, integration, and cost over present efforts in LED chip shaping and packaging. The integration of a distributed Bragg reflector (DBR) behind the active region can not only reflect the light which would otherwise be emitted into the substrate, but also enhance light extraction for modes which satisfy the resonance condition in the vertical cavity between the air interface and the DBR[5]. Forming the DBR using materials with high index contrast, such as GaAs and AlO_x, creates broadband reflectivity over the entire range of angles comprising the light extraction cone[6]. Light emitted outside the extraction cone will be trapped in guided modes which never exit the surface.

To extract guided modes, we incorporated circular Bragg gratings (CBG) etched to form the perimeter of 20 μm circular cavities. The device shown in Fig. 1 shows the circular grating as well as the DBR layers visible in the oxidation trench. Since the etched grating was only on the periphery of the light-emitting mesa, it did not spoil the internal quantum efficiency through surface recombination, as has been the case with photonic crystals etched into the same region where radiative recombination occurs[4].

The sample, grown by molecular beam epitaxy, consisted of 3 layers of InGaAs self-assembled quantum dots in the center of a 300 nm-thick GaAs spacer layer. The quantum dot layers were spaced by 12 nm. Below the spacer layer was a 4-period GaAs/AlO_x DBR centered at 1110 nm. The oxide layers were formed from the native oxide of epitaxial $Al_{0.9}Ga_{0.1}As$ during processing. The CBGs were fabricated using electron-beam lithography and chemically-assisted ion beam etching.

The integrated PL from a oxidized device with no CBG had a 2.7× enhancement over the PL from an unoxidized sample, demonstrating the role of the vertical cavity in enhancing light extraction. Devices with 525-nm (Fig. 2, red) and 360-nm (Fig. 2, green) pitch CBGs showed large PL enhancements over a device with no CBG. Resonant enhancement was as high as 11.9× at 1137 nm. The sharp peaks in the PL spectra corresponded to the guided modes which satisfied the in-plane resonances of the 20 μm diameter circular cavity (CC), with an 8.5 nm average free spectral range.

A 1st order CBG ($a = \frac{\lambda}{2n_{eff}} = 180$ nm) acts as a mirror which couples only in-plane guided waves. Therefore, we would expect that a 1st-order CBG would display no enhancement of PL. As expected, the 1st-order CBG PL was

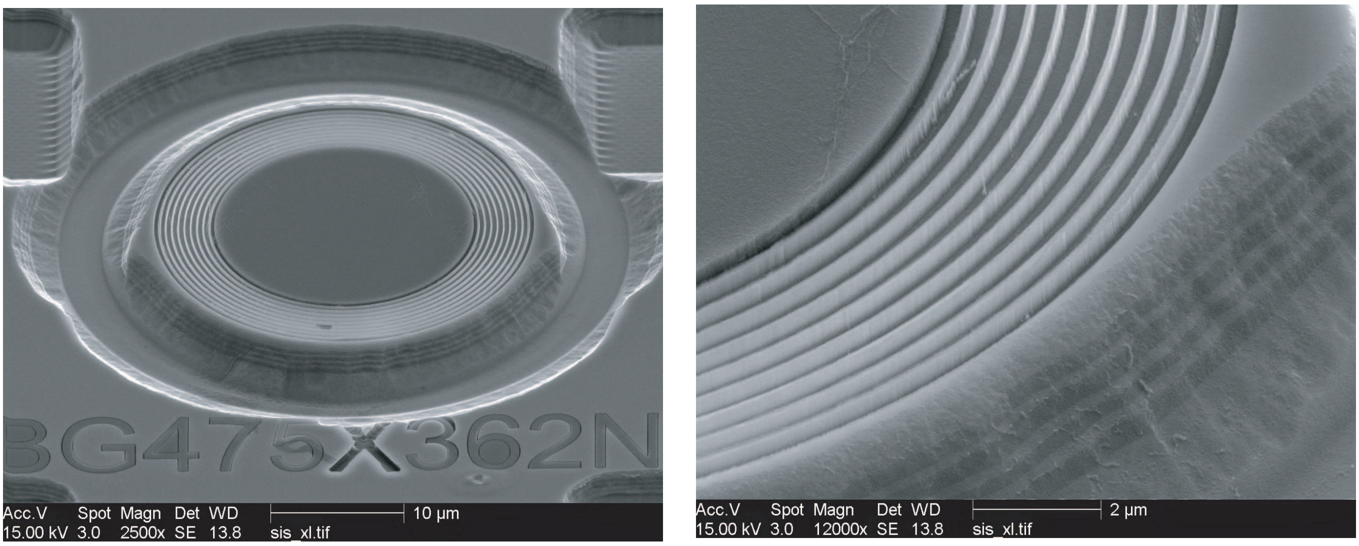

FIG. 1: Scanning electron micrograph of circular Bragg grating device.

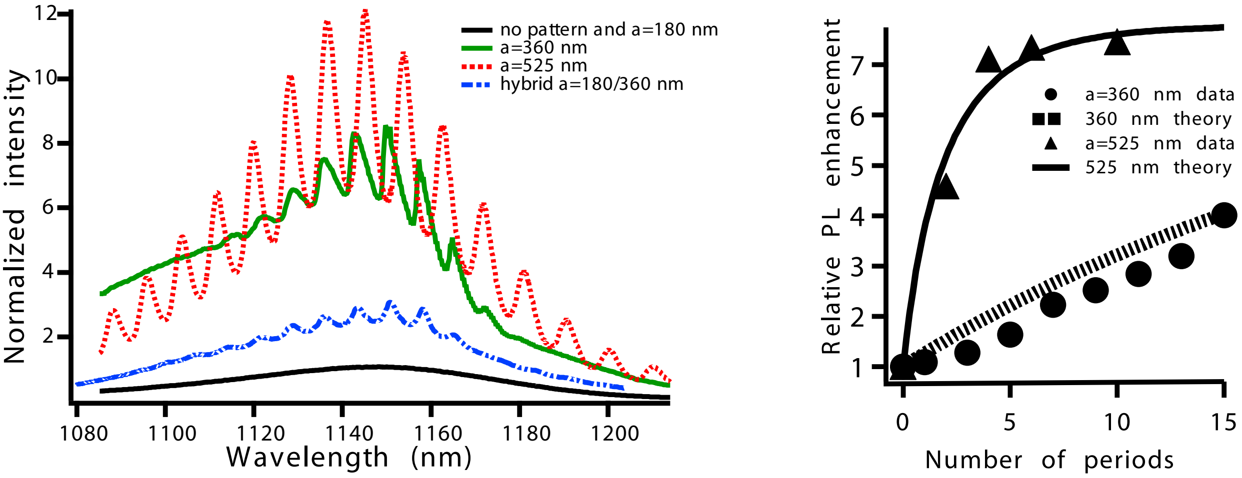

FIG. 2: LEFT: In order of increasing intensity: PL spectra for devices with no grating, a 180 nm CBG, a hybrid 180 nm / 360 nm CBG, a 360 nm CBG, and 525 nm CBG. The PL of the 180 nm CBG was indistinguishable from the PL of a device with no grating. RIGHT: Integrated PL intensity vs. number of grating periods for 525 nm-pitch and 360 nm-pitch CBGs.

indistinguishable from the PL with no grating (Fig. 2, black).

In contrast, the $m = 1$ diffraction order from a 2nd-order grating ($a = \frac{\lambda}{n_{eff}}$=360 nm) results in $k_r = 0$, and therefore couples guided waves to waves which propagate normal to the surface. Meanwhile, the $m = 2$ diffraction order couples inward- and outward-propagating guided waves, forming the standing-wave modes of the CC. Thus a 2nd-order CBG enhances PL extraction by coupling the CC modes to non-resonant radiation modes.

The integrated light extraction from the 360 nm CBGs and 525 nm CBGs is compared in Fig 2. We measured up to a 7.5× integrated extraction enhancement over the 130 nm bandwidth. We estimated the differential efficiency of a device with no CBG as $\sim 2.7/4n^2 = 0.055$ where $n = 3.5$ is the GaAs refractive index and the factor of 2.7 is the measured enhancement from the oxidized DBR. Therefore a 7.5× enhancement corresponded to an absolute external efficiency of the CBG device of ∼41%.

Clearly the 525 nm CBGs were strongly coupled while the 360 nm CBGs were weakly coupled. The 525 nm-pitch grating couples the guided mode with the vertical cavity resonant extracted mode in the frequency range of interest. As both guided and resonant extracted modes are confined to the vertical cavity, their overlap can be much greater than the overlap between guided and non-resonant radiation modes. The enhancement is approximately equal to the electric field enhancement of the resonant extracted mode electric field within the vertical cavity, determined by the Fresnel reflection coefficient at the GaAs-air interface. The solid and dotted lines (Fig. 2, right) are based on a phenomenological theory which estimates the coupling enhancement of a resonant extracted mode over a nonresonant radiation mode.

In conclusion, a seven-fold enhancement of light extraction over a 130 nm bandwidth from a semiconductor at room temperature was achieved using CBGs etched around the periphery of a vertical cavity structure. Mode extraction was maximized by momentum-matching of guided modes with resonant extracted modes. The calculated absolute external efficiency of the CBG device was ∼41%.

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