

Light concentration in photonic crystal and plasmon optical cavities

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A. Photonic Crystal optical cavities and lasers

When combined with high index contrast slabs in which light can be efficiently guided, microfabricated two-dimensional photonic bandgap mirrors and metallic plasmon resonators provide us with the geometries needed to confine and concentrate light into extremely small volumes and to obtain very high field intensities. Fabrication of optical structures has now evolved to a precision which allows us to control light within such etched nanostructures. The reduction of the size of optical components leads to their integration in large numbers and the possibility to combine different functionalities on a single chip, much in the same way as electronic components have been integrated for improved functionality in microchips. Here we describe the design, the fabrication and the characterization of functional optical devices, such as lasers, modulators, add/drop filters, polarizers and detectors based on photonic crystals, and explore the possibility of integrating these into photonic integrated systems. We will focus on the applications of these systems for optical sensors and optical data communications, and the opportunity to develop novel opto-fluidic devices.

We will show that the design and fabrication of optical structures has evolved to a precision which allows us to control light emission from etched nanostructures. For example, sub-wavelength nano-optic cavities can be used for efficient and flexible control over both emission wavelength and frequency. Similarly, nanofabricated optical waveguides can be used for efficient coupling of light between devices. This new capability enables the reduction of the size of optical components and leads to their integration in large numbers, much in the same way as electronic components have been integrated for improved functionality to form microchips. As high-Q optical and electronic cavity sizes approach a cubic half-wavelength the spatial and spectral densities (both electronic and optical) increase to a point where strong light-matter coupling becomes possible. We have developed new optical cavities with Q values above 10,000, and mode volumes as small as two to three cubic half wavelengths. With these designs, we have demonstrated optically pumped photonic crystal lasers, strong coupling between quantum dots and photonic crystal cavities, as well as spectroscopic analysis tools for sub-picoliter volumes.

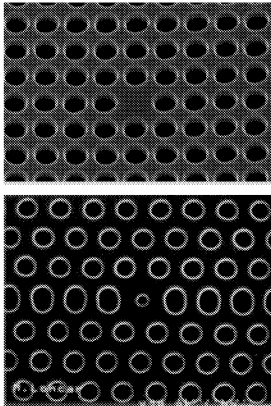


Figure 2. Two different photonic crystal laser designs

B. Surface plasmon enhanced light-emitters

We have developed a method to enhance the quantum efficiency of light emitting diodes through the energy transfer between quantum wells (QWs) and surface plasmons (SPs). SPs can increase the density of states and the spontaneous emission rate in the semiconductor³⁻⁹. So far, the enhancement of light emission by SP-QW coupling has not been observed directly for visible light. Large enhancements of the internal quantum efficiencies (η_{int}) were measured when silver or aluminum layers are deposited 10 nm above an InGaN light emitting layer, whereas no such enhancements are obtained from gold coated samples. Our results indicate that the use of SPs lead to a new class of very bright LEDs, and highly efficient solid-state light sources.

Figure 3 shows typical luminescence spectra from an InGaN/GaN QWs separated from silver, aluminum, and gold layers by 10 nm GaN spacers. The luminescence peak of the

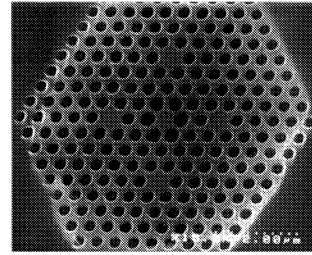


Figure 1. Five coupled Nanocavities

uncoated wafer at 470 nm is normalized to 1, and a 14-fold enhancement in peak PL intensity is observed from the silver coated emitter. The luminescence intensity integrated over the emission spectrum is increased by 17 times. 8-fold peak intensity and 6-fold integrated intensity enhancements are obtained from aluminum coated InGaN QW, whereas the PL is not increased after gold coating. A small increase in the luminescence intensity might be expected after metallization since the metal reflects pump light back through the QW, doubling the effective path of the incident light, but differences between gold and silver reflectivities at 470 nm cannot explain the large difference in the measured enhancement alone. Fig. 4 shows the enhancement ratios of PL intensities with metal layers separated from the QWs by 10 nm spacers as a function of wavelength. We find that the enhancement ratio increases at shorter wavelengths for Ag samples, while it is independent of wavelength for Al sample. The PL enhancement after coating with Ag and Al can be attributed to strong interaction with SPs. Electron-hole pairs excited within the QW couple to electron vibrations at the metal/semiconductor interface when the energies of electron-hole pairs in InGaN ($\hbar\omega_{\text{InGaN}}$) and of the metal SP ($\hbar\omega_{\text{SP}}$) are similar. Then, electron-hole recombination may produce SPs instead of photons, and this new recombination path increases the spontaneous recombination rate.

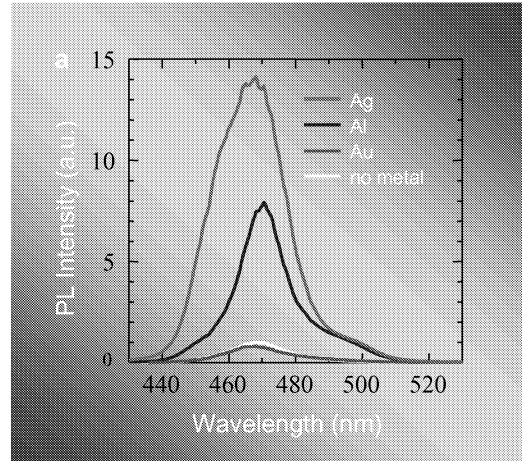


Figure 3. Luminescence results from InGaN quantum wells after coating with different metal layers

PL intensities of Al and Ag coated samples were also found to strongly depend on the distance between QWs and the metal layers whereas Au coated sample did not. Al and Ag

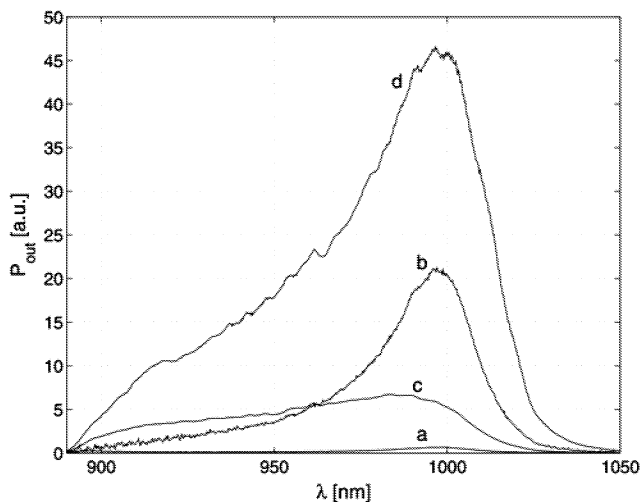


Figure 4. Photoluminescence results from InGaAs quantum wells (a) as grown, (b) after substrate removal, (c) after silver coating and (d) after patterning of the silver surface with an appropriate grating.

samples show exponential increases in luminescence intensity as the spacer thickness is decreased, whereas no such improvement was measured in gold coated QWs. If the metal/semiconductor surface were perfectly flat, it would be difficult to later extract light from the SP, a non-propagating evanescent wave. However, roughness and imperfections in evaporated metal coatings can scatter SPs as light. We measured a modulation depth of the Ag surface of approximately 30-40 nm while the GaN roughness was below 10 nm. We found a doubling of the emission from lithographically defined grating structures, when the periodicity of these is tuned to the emission wavelength. This measurement suggests that the size of the metal structure determined the SP-photon coupling and the light extraction. Similar results are obtained on InGaAs quantum well samples emitting in the near-infrared region at 980nm (Figure 4)