Observation of Whispering Gallery Resonances in Circular and Elliptical Semiconductor Pillar Microcavities

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Abstract — We observed whispering gallery resonances in semiconductor micropillars by employing geometry in which both excitation and collection of emission is in a direction normal to the sidewall surface of the pillars. The spectral positions of the peaks are found to be in good agreement with the results of numerical modeling performed by finite difference time domain technique. The quality factors of whispering gallery modes ($Q \sim 20000$ for the 4–5 $\mu$m circular pillars) are found to be well in excess of $Q$-factors for the low $k$-vector “photonic dot” states measured from the same pillars. Due to high $Q$-factors and small modal volumes such whispering gallery resonances can be used in cavity quantum electrodynamics experiments.

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Several groups demonstrated recently \cite{1–3} strong coupling regime between cavity mode and individual quantum dot resonance in photonic microstructures. The design of the optical cavity for these experiments requires a combination of small modal volumes and ultrahigh quality ($Q$) factors of resonances. The advantages provided by whispering gallery modes (WGMs) for such experiments have been demonstrated \cite{3} in the case of semiconductor microdisks. In this work we observed for the first time that semiconductor pillar microcavities with well defined “photonic dot” states \cite{4, 5} simultaneously possess high-$Q$ ($> 10^4$) WGM resonances. The combination of optical properties of such pillars is unique in terms of possible cavity quantum electrodynamics experiments since it allows observing coupling with dots with different spatial location inside the pillars. In addition we observed modes with $Q \sim 5000$ in very small pillars with extremely high ellipticity ($2.5 \times 1.5 \mu$m size).

Our microcavity structure consists of 27 pairs of alternating AlAs/GaAs layers in the bottom distributed Bragg reflector and 20 repeats on top. The one-wavelength cavity contains one layer of InAs quantum dots of density $\sim 5 \times 10^9 \mu$m$^{-2}$ positioned at the anti-node of the optical field. The quantum dots serve as an internal light source, enabling observation of the WGMs. The samples were processed into 1–10 $\mu$m diameter pillars using a combination of electron beam lithography and inductively coupled plasma etching. A scanning electron micrograph of a 4 $\mu$m circular pillar is shown in the inset of Fig. 1. The structure was cleaved to enable easy optical access to the sidewalls of the pillars. The distance between the pillars and the cleaved edge of structure was in the 1–5 $\mu$m range. The experiments were performed under high power conditions ($\sim 1$ mW) where emission from single quantum dots is not resolved.

It is well documented that excitation and collection of PL emission in the vertical direction through the Bragg mirrors in such structures result in the observation of “photonic dot” states \cite{4, 5} represented by the peaks in the blue spectra (labeled top to indicted detection through the top mirror) in Fig. 1. The formation of such states with nearly zero in-plane $k$-vector is a result of the coexistence of the strong vertical confinement produced by the Bragg mirrors with the additional lateral confinement in the pillars. It is also well known that in cylindrical and spherical cavities light can be trapped in high in-plane $k$-vector WGM states \cite{6} with very high quality ($Q$) factors due to total internal reflection inside the resonator. In the present work we realised the first observation of such high $Q$ states in semiconductor micropillars by employing geometry in which both excitation and collection of emission is in a direction normal to the sidewall surface, as shown schematically at the top of Fig. 1. In the emission spectra we observed a series of nearly equidistant peaks, a fingerprint of WGMs, illustrated by the red spectra in Fig. 1 and Fig. 2. The separation between the peaks was found to be inversely proportional to the diameter of the pillars as illustrated by the comparison of Fig. 1 and Fig. 2, taken for 4 and 5 $\mu$m pillars respectively.
The \( Q \)-factors of WGMs were investigated using a 0.85 m double spectrometer and gave \( Q \) values of 20000 for the 4–5 \( \mu \)m circular pillars, well in excess of \( Q \)-factors (6-8000) for the low \( k \)-vector “photonic dot” states measured from the same pillars.

High-\( Q \) WGMs (\( Q \)-values of 12,000) have been observed in semiconductor microdisk laser structures [7–9] in which high sidewall smoothness was obtained by optimisation of the wet etching process. In laser disk structures the sidewall confinement combines with the efficient vertical confinement at the semiconductor/air interfaces to produce the WGMs. In this respect the high \( Q \)-values of the WGMs observed in our work in microcavity pillars are surprising since the modulation of index between the one wavelength GaAs cavity regions and the AlAs/GaAs distributed top and bottom Bragg reflectors is much smaller compared to that at the air/semiconductor boundary in microdisks.

Numerical modeling of WGM effects was performed using three-dimensional finite difference time domain (FDTD) FullWave\textsuperscript{TM} software [10]. We used a simplified model of a disk (index 3.5) with the one-wavelength thickness. The source wave front was generated on the half a wavelength square plane inside the disk placed perpendicular to its surface at small depth to effectively excite WGMs. The discretization grid parameter was equal to 1/16 of the center pulse wavelength \( \lambda = 940 \) nm in each dimension. We used a femtosecond transverse electric (TE) polarized built-in source to

Figure 1: Circular 4 \( \mu \)m pillar microcavity: emission spectra detected from sidewall surface (red) and from the top mirror (blue).

Figure 2: Circular 5 \( \mu \)m pillar microcavity: experimental WGM spectra detected from sidewall surface (red) and FDTD modeling.

Figure 3: Elliptical 5 \times 3 \( \mu \)m pillar microcavity: emission spectra detected from sidewall surface. Inset shows an SEM image of a pillar.

Figure 4: Elliptical 2.5 \times 1.5 \( \mu \)m pillar microcavity: emission detected from sidewall surface. WGM resonances are indicated.
generate a comb of WGM resonances with various radial \((n)\) and angular \((l)\) mode numbers. To calculate the spectra of WGMs we used a Fourier transform of the electrical field averaged over several points inside the disk in the vicinity to its surface.

As illustrated in Fig. 2 for 5\,\mu m disk the calculations predict nearly equal separation between sequential modes with the same radial number \((n = 1)\) and same (TE) polarization. This separation (18.7 meV) is found to be in very good agreement with the experimentally observed separations between the WGMs peaks. Close inspection of the experimentally observed mode energies in Fig. 1 and Fig. 2 shows however that the separations between WGMs are increased at lower energy. A full theoretical description of the field and energy distribution of the WGMs requires the effects of penetration of the electromagnetic field into the mirrors as well as the effects of absorption introduced by the quantum dots to be taken into account. These points will be addressed by the more accurate modeling in progress.

Asymmetric WG resonators are expected to be particularly interesting: new phenomena such as chaos-assisted tunneling and dynamical localization [11] have been theoretically predicted. Micrographs of 5 \times 3 \mu m and 2.5 \times 1.5 \mu m elliptical pillars are shown in the insets of Fig. 3 and Fig. 4 respectively. Spectra measured from the sidewall surfaces are presented in Fig. 3 and Fig. 4. They illustrate deterministic rather than chaotic WGM resonances.

In conclusion, due to the small modal volume and high \(Q\)-factors (up to 20,000 at 4\,\mu m circular and 5000 in e.g., the 2.5 \times 1.5 \mu m micropillar in Fig. 4), as well as due to their intrinsic interest, the WGMs observed here have potential for future experiments on the observation of strong coupling with individual quantum dots.

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