Optical Cavity Modes in Micro-Pyramids

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Abstract: We report on the fabrication and investigation of pyramidal GaAs micro-cavities on top of a Bragg mirror. A finite-difference time-domain simulation supports the experimentally found optical mode structure for such a cavity shape.

OCIS codes: (230.5750) Resonators; (230.1480) Bragg reflectors; (220.4000) Microstructure fabrication

1. Introduction

An optical interaction of spatially separated quantum dot (QD) states can be mediated via a micro-cavity mode [1]. Such an optical coupling requires high-quality (Q) micro-cavities with small mode volumes. We suggest GaAs pyramidal micro-cavities placed on top of AlAs/GaAs distributed Bragg reflectors (DBRs) to be promising candidates for such a task [2-4]. The fabrication of the pyramid facets by means of a wet-chemical etching process offers a high diversity to control the geometry, especially the facet slope and size.

2. Fabrication and optical measurement

The pyramids were manufactured from a layer structure grown by molecular-beam epitaxy. An AlAs/GaAs DBR designed for 950 nm was grown on a GaAs substrate followed by a GaAs target layer with embedded InAs QDs, a 100 nm thick AlAs sacrificial layer and a GaAs capping layer. Quadratic masks of resist aligned along the [100] and [010] crystallographic orientations were achieved by electron-beam lithography.

The key issue in the facet formation was the wet-chemical etching process. The etchant was based on phosphoric acid (H_3PO_4), hydrogen peroxide (H_2O_2) and pure water. The composition of the etchant determined the ratio of the etching rates in GaAs and AlAs. Thus, certain facet slopes in the GaAs capping and target layer developed when the etching solution reached the AlAs sacrificial layer which induced a strong undercut [5]. When stopping the etching process before the AlAs sacrifical layer was etched through vertically connected pyramids with one pyramid in the target layer and a reversed one on top of it in the capping layer could be fabricated, see the scanning electron microscope (SEM) image in Fig. 1(a), [3,4]. Keeping the layer structure in the etchant long enough resulted in a single pyramid on top of the DBR as shown in Fig. 1(b).

For an optical characterization we studied these single pyramids in a confocal micro-photoluminescence (µ-PL) set-up. A luminescence signal was obtained in the wavelength range from 870 nm to 1000 nm where the QDs and the wetting layer (WL) were emitting under continuous-wave laser excitation. Typically such a µ-PL spectrum showed several peaks. To sort out peaks simply caused by spectral fluctuations in the emission of the small QD ensemble (a single pyramid contains only a few hundred QDs) we analysed the thermal shift of these peaks in a temperature range between 50 K and 200 K. With increasing temperature there was a small red-shift of the cavity mode peaks due to the weak temperature dependence of the refractive index whereas the emission of the WL and QDs showed a strong thermal shift related to the decreasing effective band gap. First results were published in [2].

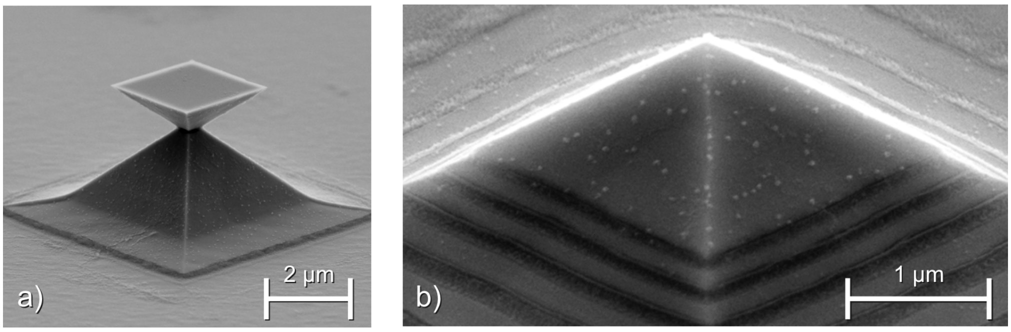

Fig. 1. SEM images showing (a) a pyramid with a reversed pyramid on top and (b) a single pyramid with a base length of 2.4 µm.

At least six different cavity mode peaks were clearly observable in the µ-PL spectrum of a pyramid with a base length of 2.4 µm and a height of 1 µm, see arrows in Fig. 2(a). Q-factors of these modes were calculated by Lorentzian fits reaching values up to 650.

3. Comparison with finite-difference time-domain simulation

The base length of the studied GaAs pyramids was about seven times larger than the resonant wavelengths therein and hence modes of high order and a big mode density have been expected. A finite-difference time-domain (FDTD) simulation with a freely available software package was implemented to get an idea of the mode structure [6]. For simplification the pyramid with a quadratic base plane was approximated by a cone with rotational symmetry.

Fig. 2(b) shows the wavelength positions and their Q-factors of resonant cavity modes calculated in a cone on top of a DBR with an equivalent volume to a pyramid of 2 µm base length. The FDTD simulation predicted many modes but as Fig. 2(b) indicates there were only few with relatively high Q-factors (comparable to the experimental values). Consequently we believe that we measured single cavity modes in these pyramids whereas the majority of modes were not observable due to poor Q-factors.

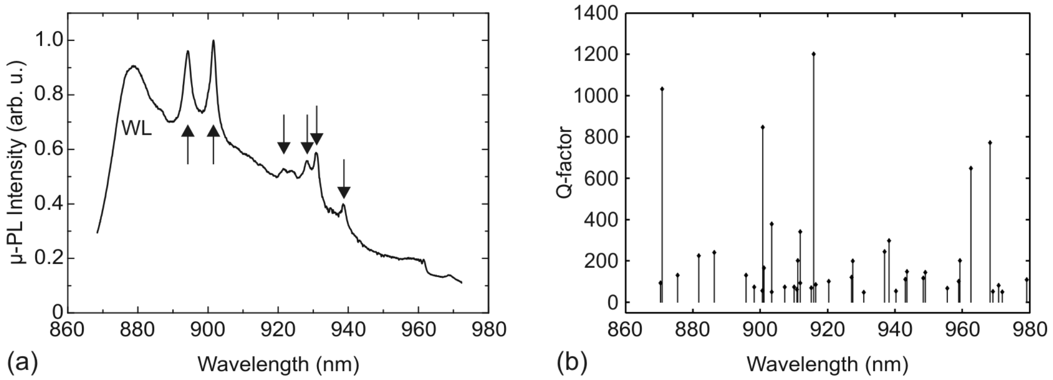

Fig. 2. (a) µ-PL spectrum of a pyramid with base length 2.4 µm showing cavity modes indicated by arrows. (b) Q-factors for different modes in a simulated cone with radius 1.13 µm.

4. Conclusion

We studied optical cavity modes in GaAs pyramids on top of AlAs/GaAs DBRs. The mode character of these peaks in the µ-PL spectrum was confirmed by means of temperature dependence. With the results of a FDTD simulation we classified the peaks to be single cavity modes while other modes in this high order range were not visible due to their insufficient Q-factors.

5. References

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