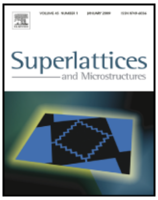
Superlattices and Microstructures 47 (2010) 83–86

Contents lists available at ScienceDirect

Superlattices and Microstructures

journal homepage: www.elsevier.com/locate/superlattices



Reversed pyramids as novel optical micro-cavities

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ARTICLE INFO

Article history:
Available online 18 July 2009

Keywords:
GaAs Micro-cavity
Reversed pyramids
Wet-chemical etching

ABSTRACT

Pyramidal micro-cavities represent a novel promising class of semiconductor optical cavities. In contrast to our previous approach based on pyramids sitting on distributed Bragg reflectors, we investigate reversed freestanding GaAs pyramids. The latter are achievable by a wet-chemical etching process where an AlAs sacrificial layer in the epitaxially grown layer structure is used. In freestanding GaAs pyramids, light is simply confined by total internal reflection at the interface of the high refractive index material GaAs to the surrounding. Due to strong optical confinement within the pyramidal shape, small mode volumes are expected. Quality factors up to 3000 were measured in first structures. However, simulations suggest the possibility of much higher values. Therefore, these freestanding pyramids are promising for an optimized ratio between quality factor and mode volume, which is crucial for quantum-optical applications.

In order to study efficient light-matter interaction with single quantum dots inside micro-cavities, an optimized ratio of quality (*Q*) factor and mode volume is required [1,2]. Light confinement by Bragg reflectors (DBRs) tends to enlarge the cavity's mode volume due to the penetration of the electromagnetic field into the adjacent Bragg stacks. Total internal reflection provides an alternative for light confinement inside semiconductor micro-structures, such as whispering-gallery modes (WGM) in micro-disks. The pyramidal cavities discussed below try to fill the gap between conventional resonators, which comprise spatially extended modes, and WGM cavities where the light is confined close to the surface.

So far, self-assembled pyramids of GaN or ZnS and wet-chemically etched pyramids of GaAs relied on both, total internal reflection at the facets and DBRs underneath [3–5]. In this work, we present

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doi:10.1016/j.spmi.2009.07.011

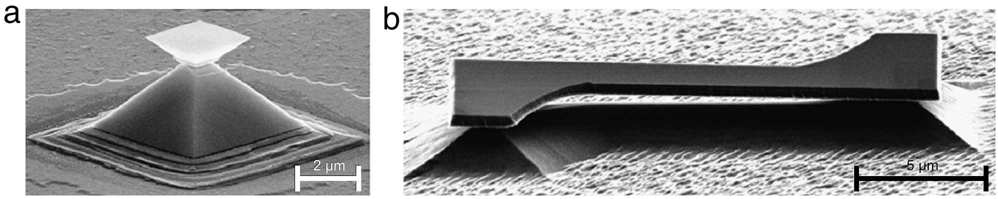

Fig. 1. Scanning electron microscope images of freestanding GaAs micro-pyramid structures: (a) Reversed pyramid on top of a pyramidal socket with a GaAs/AlAs DBR underneath. (b) Reversed pyramids vertically connected by a cantilever bridge.

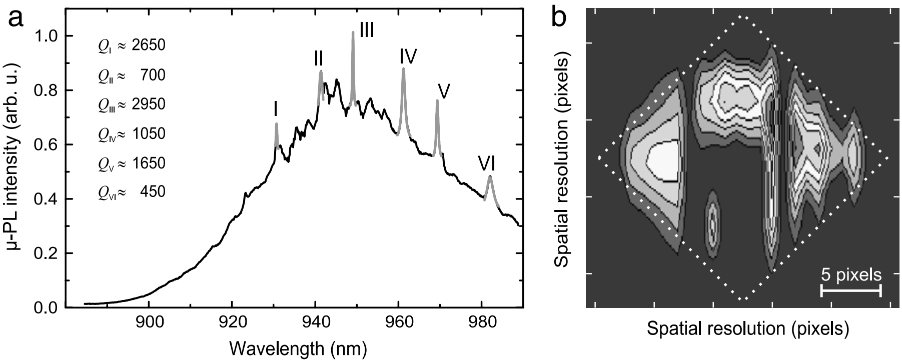

Fig. 2. μ-PL measurements: (a) Spectrum of a reversed pyramid revealing high-Q factors (base length: 2.4 μm, facet angle 44°, temperature: 80 K). (b) Typical spatially resolved signal at the wavelength of an optical cavity mode; a diamond-shaped intensity distribution (within dotted square) represents the pyramid's base plane.

freestanding reversed GaAs pyramids as micro-cavities where light is kept inside only due to internal reflection at the non-parallel facets within the high refractive-index material ($n_{\mathrm{GaAs}} = 3.5$).

The pyramids were shaped by a wet-chemical etching process with a solution of phosphoric acid, hydrogen peroxide and pure water [5,6]. As an initial layer structure, this fabrication method requires an epitaxially grown AlAs sacrificial layer (100 nm) upon a GaAs substrate, followed by a capping GaAs layer with a thickness equal to the later reversed pyramid height (1 μm). For an optical characterization with luminescence afterwards, InAs quantum dots as internal broad-band light source were embedded in two layers (500 nm and 666 nm from top) within the top GaAs layer, i.e., into the later freestanding pyramids. The etching process was stopped just before the AlAs sacrificial layer underneath the reversed pyramids was etched through; see Fig. 1(a). (In this example an additional distributed Bragg reflector (DBR) below the GaAs socket pyramid was grown, thus leading to a vertically coupled resonator.) Mechanically stable freestanding pyramids were found for cross-sections larger than approx. 150 nm of the AlAs sacrificial layer.

By means of square etching masks, pyramids with a quadratic base were achieved [5,6] and, with an appropriate mask design, even reversed pyramids laterally connected by a cantilever bridge could be realized; see Fig. 1(b).

Micro-photoluminescence (μ-PL) of single reversed pyramids was measured with a confocal set-up (excitation wavelength at 532 nm or 825 nm). Fig. 2(a) shows the μ-PL spectrum of such a freestanding pyramid. On top of the emission of the quantum dot ensemble sharp peaks can be found. The labelled maxima clearly confirmed their cavity mode origin by their characteristic thermal behavior [5]. Thus, Q factors up to 3000 for cavity modes in the reversed pyramids were determined by Lorentzian fits to the experimental data.

Measurements using a charge-coupled device camera behind the spectrometer allow for a spatially resolved detection of the pyramids' luminescence along the direction of the spectrometer entrance

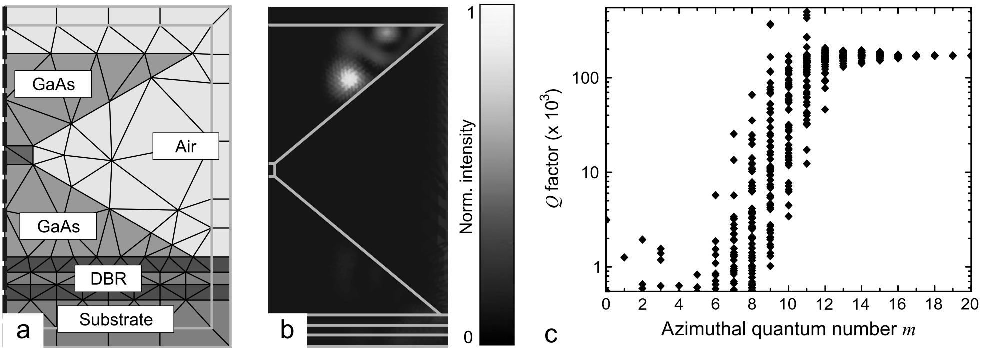

Fig. 3. Simulation of cones based on the finite element method: (a) Radial cut with finite elements through the rotational symmetry of the simulated geometry. (b) Intensity distribution for a whispering gallery-like mode with a cone angle of 40°. (c) Strong dependency of Q factor on the azimuthal quantum number m of the optical mode (radius 1 μm, cone angle 30°).

slit. A two-dimensional distribution can thus be reconstructed through subsequent records of parallel tracks of the pyramid which, for this purpose, is shifted in tiny steps by piezo elements. After computing the relative maxima out of the row data, a certain pattern of the intensity distribution appears at the wavelength of a cavity mode; see Fig. 2(b). High relative intensities appear at spatial positions where high intensities within the micro-structure are located and/or where high optical losses occur. In addition to the temperature dependence, the regular intensity pattern confirms the cavity mode nature of the peaks in the spectrum. Moreover, the square shape of the pyramid's base plane can be recognized as a diamond in the intensity distribution of Fig. 2(b) within the dotted lines. It has to be noticed that strong intensities were mainly found towards the edges of the square and never in the middle of the square shape.

Apart from optical measurements, a model of the structure including the socket was set up but reduced to rotational symmetry due to computational resources; i.e., the pyramids are replaced by cones. For the implementation, we used the software package JCMsuite based on finite elements [7]. A radial cross-section with the initial mesh prior to adaptive refinements is shown in Fig. 3(a). The cavity modes in this double cone-shape structure found by plane wave excitation mainly showed intensity localized in (the rim of) the upper freestanding cone, whereas in the socket cone underneath no (or hardly any) intensity could be observed, see Fig. 3(b). The light is kept mainly in the upper cone because no (or only one) DBR pair is sitting below the socket cone. As a consequence, light cannot be confined in this lower cone due to the lack of reflection at the base plane. (A DBR stack of at least more than ten pairs, or a material with high refractive index contrast, would be required.)

On the other hand, the light confinement in the upper freestanding structure must be purely caused by internal reflection at the GaAs/air interface. And, although the circular base plane differs from the square base in the experiment, in both cases, no intensity was found in the center of the base plane, compare Fig. 2(b) with Fig. 3(b). Hence, modes in both geometries can be considered similar in their structure, i.e., WGM like. For that reason, the freestanding geometry is expected to achieve smaller mode volumes than the original pyramid or cone on top of a DBR into which the light field penetrates [8], although even the latter already reached mode volumes in the order of seven cubic wavelengths in the medium, which is comparable with thin micro-pillar cavities [7].

In Fig. 3(c) the Q factors of all calculated cavity modes for one geometry are plotted vs. the azimuthal quantum number m which describes the electromagnetic field distribution along the circumference according to $\exp(im\phi)$. The Q factor dramatically increases up to $Q > 100{,}000$ for high m values. This indicates high-Q whispering gallery modes in the rotational symmetry.

Owing to anisotropic effects in GaAs, a rotational symmetry is difficult to achieve by wet-chemical etching. But slightly modified WGMs with $m \geq 8$ and $Q > 30{,}000$ would be supported in feasible pyramids with hexagonal or octagonal base planes for diagonals ≈2 μm. In such structures, the ratio between Q and mode volume could be optimized (e.g, by varying the facet angle). Therefore, they should be promising candidates for future quantum-optical applications.

Acknowledgments

This work has been performed within project A2 of the DFG Research Center for Functional Nanostructures (CFN). It has been further supported by a grant from the Ministry of Science, Research and the Arts of Baden-Württemberg (Az: 7713.14-300).

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