GaAs micro-pyramids serving as optical micro-cavities

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Abstract. An efficient light-matter coupling requires high-quality (Q) micro-cavities with small mode volume. We suggest GaAs micro-pyramids placed on top of AlAs/GaAs distributed Bragg reflectors to be promising candidates. The pyramids were fabricated by molecular-beam epitaxy, electron-beam lithography and a subsequent wet-chemical etching process using a sacrificial AlAs layer. Measured Q-factors of optical modes in single pyramids reach values up to 650. A finite-difference time-domain simulation assuming a simplified cone-shaped geometry suggests possible Q-factors up to 3600. To enhance the light confinement in the micro-pyramids we intend to overgrow the pyramidal facets with a Bragg mirror—results of preliminary tests are given.

Keywords: pyramidal micro-cavity, micro-pyramids, cone-shaped resonator, finite-difference time-domain simulation.
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INTRODUCTION

Light-matter interactions can be enhanced in micro-cavities. Potential applications are single photon emitters [1] and quantum information processing, e.g. optical resonators to control a coupling of spatially separated quantum dots (QDs) [2].

Here we present pyramidal micro-cavities on top of AlAs/GaAs distributed Bragg reflectors (DBRs). The fabrication method allows to control the size and facet slope quite easily. By means of simulation results we classified the peaks in micro-photoluminescence (μ-PL) spectra of single pyramids to be individual cavity modes [3]. An improved light confinement in the pyramids should be possible by DBR overgrowth. First facets were overgrown by molecular-beam epitaxy (MBE) to investigate suitable fabrication conditions.

The initial layer structure with embedded InAs QDs in the latter GaAs pyramids was grown by MBE. We aligned quadratic masks along certain crystallographic axes by electron-beam lithography and achieved the formation of pyramids by means of an AlAs sacrificial layer in a wet-chemical etchant based on phosphoric acid [4, 5]. For μ-PL measurements we excited the embedded InAs QDs with a laser ($\lambda = 532\,nm$). Figure 1 shows a typical spectrum of the QD emission, which is modified by the optical cavity modes (and the wetting layer (WL) emission). The modal nature of the peaks was proved by temperature-dependent measurements [6]. Q-factors as high as 650 have been found for a pyramid with a base length of 2.4 μm, 550 for 1.6 μm and 300 for 1.1 μm, respectively.

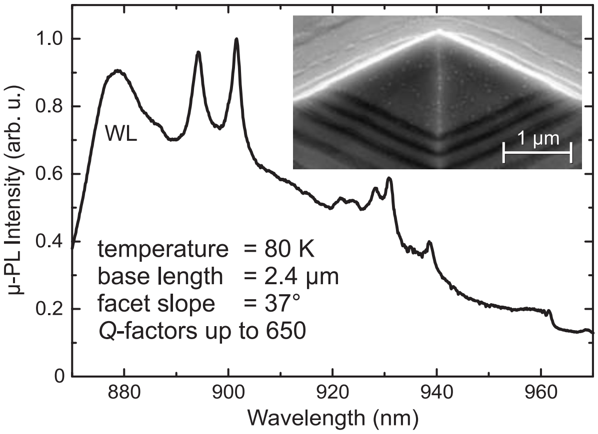

FIGURE 1. Micro-photoluminescence spectrum of a single pyramid; the inset shows an electron microscopic image of a single pyramid.

FDTD SIMULATION

In order to estimate the mode density and maximum Q-factors we set up a simulation based on finite-difference time-domain (FDTD) methods. For computational reasons a cone-shaped geometry with rotational symmetry was chosen. Figure 2 shows Q-factors for different modes in the wavelength range of the QD emission in the experiment. The circular base area of the cone equals a quadratic base of edge length 2 μm. The modes' Q-factors in the simulation recovered an interesting distribution: more than two thirds of the 29 found modes have a Q value below 20 % of the maximum Q-factor, i.e., 3600 in this case. The inset of Fig. 2 displays the intensity distribution of a mode with relatively high Q-factor.

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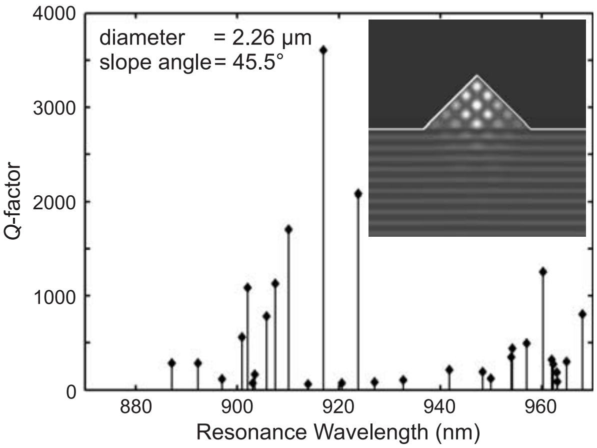

FIGURE 2. Q-factors of the calculated resonance modes; the inset shows the intensity distribution for a mode with high Q-factor.

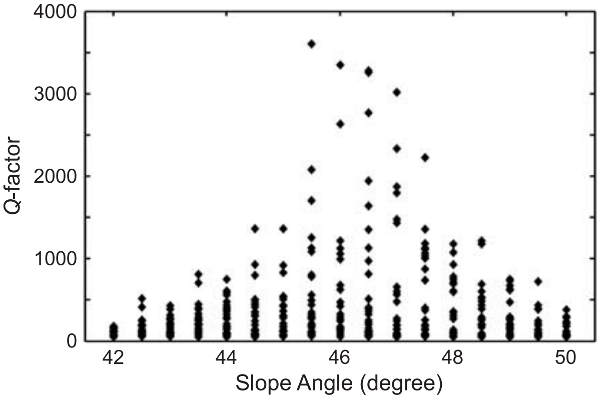

FIGURE 3. Q-factors of resonance modes in dependence on the slope angle of the simulated cone.

Although the mode structure in pyramids may differ slightly from modes in cones we find a density of high-Q modes in the same order as modes in our experiments. For this reason we actually conclude to detect single modes in the micro-pyramids whereas low-Q modes disappear in the QD emission.

Furthermore, we computed the modes' Q-factors in dependence on the slope angle of the cone. Figure 3 shows that highest Q-factors were found for angles around 46°, in particular the maximum Q-factor of 3600 has been calculated for a slope angle of 45.5°.

DBR OVERGROWTH

In order to enhance the light confinement in the micro-pyramids we are trying to overgrow them with another AlAs/GaAs DBR on top. Preliminary tests revealed that the possibility of a smooth DBR overgrowth by MBE depends quite crucially on the facet slope: Up to a slope of 40° the interfaces of the DBR were still planar and parallel to the initial facet, see Fig. 4 (left). For the latter a thickness of 95 % compared to the non-tilted plane was measured. For an angle of 64° the overgrowth was not smooth anymore, crystallographic planes partially appeared and thus small steps in the facet developed, see Fig. 4 (right). Therefore, an overgrown layer structure with such defects seems to be unsuitable as a DBR.

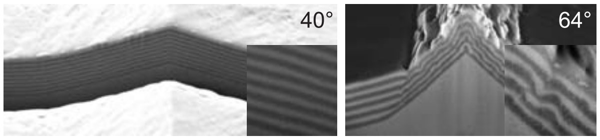

FIGURE 4. Overgrowth of layer structure on tilted facets for slope angles of 40° and 64°.

An overgrowth of properly prepared pyramids with small slope angle is underway. The overgrown pyramid should exceed the Q-factor of a single pyramid for which values up to 650 were measured so far.

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