Single photon emitters based on hybrid microcavities with InAs/Al$_X$Ga$_{1-X}$As quantum dots

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Abstract. We report on fabrication by molecular beam epitaxy and optical studies of hybrid semiconductor-dielectric micropillar structures with distributed Bragg reflectors and a microcavity containing InAs/AlGaAs quantum dots. The single photon emission in the visible spectral range with the autocorrelation function g(2)(0)<0.2 is detected in such structures with a photon count rate above 1 MHz.

1. Introduction

Recently, the sources of single photon emission and entangled pairs of photons have been intensively developed for applications in quantum cryptography and quantum computing industry. The fabrication of single-photon emitters based on heterostructures with either InAs/InGaAs [1-3] or InAs/InAlGaAsP [4-5] quantum dots (QDs) have been reported for telecommunication spectral bands (1.3 and 1.55 µm). Less developed are bright single-photon emitters intended for red part of the visible spectral range, which is suitable for the realization of protected lines of atmospheric optical communication and also covers the region of high sensitivity of most efficient single-photon avalanche photodiodes based on silicon. Until recently, single-photon emission in this range has been achieved either using InP based QDs [6-7] or GaAs QDs grown by droplet epitaxy [8]. The structures of first type suffer from a lack of a lattice matched binary distributed Bragg reflector (DBR) system with high contrast of refractive index that complicates growth of cavity structures, while the droplet-induced QD formation requires precise tuning of growth parameters.

One more promising approach to development of the efficient single-photon emitters for the red part of the visible spectral range can be fabrication of cavity heterostructures based on InAs/AlGaAs QDs, whose emission wavelength can be tuned in a widest spectral range between 650 nm and 1000 nm by only varying Al content in the AlGaN barrier layers [9-10]. The potential advantage of this approach is also availability of well-developed epitaxial technique for the Stranski-Krastanow QD formation in the InAs/AlGaAs material system. On the other hand, the available lattice-matched DBR system for such heterostructures is AlGaAs/AlAs, whose refractive index contrast progressively decreases with an increase of Al content in the AlGaAs layers. This circumstance set a limit to the shortest wavelength of bright single-photon emission achievable in this material system.

In this paper, we investigate emission properties of a microcavity structure with InAs/AlGaAs QDs, focusing on elucidation of the single-photon emission characteristics of individual InAs/AlGaAs QDs and exploration of the possibility to use dielectric DBR instead of the AlGaAs/AlAs one.
2. **Experiment and structures**

A semiconductor part of the hybrid structure, grown by molecular beam epitaxy, contains 19 periods of GaAs/Al\(_{0.3}\)Ga\(_{0.7}\)As quarter wavelength pairs, which form bottom DBR and an Al\(_{0.3}\)Ga\(_{0.7}\)As cavity with a layer of InAs/AlGaAs QDs in the middle (figure 1). A height of the 1\(\lambda\) cavity is 224 nm. Thicknesses of the GaAs and Al\(_{0.3}\)Ga\(_{0.7}\)As DBR constituting layers are 56 and 62 nm correspondingly. The top DBR is formed after growth by magnetron sputtering and consists of 3 periods of 125 nm SiO\(_2\) and 91 nm Ta\(_2\)O\(_5\). At the last technological stage, submicron size micropillar structures were formed by photolithography and reactive ion dry etching (figure 2).

![Figure 1](image1.png)  
**Figure 1.** Cross-section transmission electron microscopy image of the as-grown heterostructure with the 19 periods of the GaAs/Al\(_{0.3}\)Ga\(_{0.7}\)As bottom DBR and the 224 nm Al\(_{0.3}\)Ga\(_{0.7}\)As cavity with the QDs insertion in the middle.

![Figure 2](image2.png)  
**Figure 2.** Scanning electron microscopy image of the micropillar structure with a top dielectric mirror containing 3 periods of SiO\(_2\)/Ta\(_2\)O\(_5\) pairs.

Micro-photoluminescence measurements were performed in a standard confocal optical scheme with a 50x micro-objective and a grating monochromator equipped with a liquid-nitrogen cooled CCD camera (spectral resolution is estimated as ~90 \(\mu\)eV). Both cw and picosecond pulse lasers with the emission wavelength 404 nm were used for the PL excitation. Photon correlation measurements were performed with a Hanbury Brown – Twiss intensity interferometer exploiting two single-photon avalanched Si photodiodes with a time resolution better than 40 ps. The measurements were performed at the 8 K temperature in a continuous flow He cryostat with a nanopositioning piezo-driver.

3. **Results**

As compared to emission of a semiconductor heterostructure with only bottom DBR the hybrid structure emission has significantly narrower spectrum with full width at half maximum about 1 meV and a narrow reflection dip, which is characteristic of a DBR microcavity (figure 3).
Figure 3. Bottom curves represent photoluminescence spectra of the as-grown structure (dashed curve) and of the hybrid structure with top dielectric DBR (solid curve). An upper dotted curve represents reflectivity spectrum of the hybrid structure.

The surface QDs density estimated from atomic force microscopy measurements of uncapped QD structures is as low as \( \sim 10^{10} \text{ cm}^{-2} \) and has fluctuations at a submicron size scale. As a result, the fabricated array of several hundreds of micropillars includes cavities with essentially different amounts of QDs. For measurements, we chose several micropillars with spectrally resolved single-QD emission lines located within the microcavity resonance, where one spectral line was strongly dominating (figure 4). We assume that these bright lines may be attributed to QDs situated close to the center of the cavity mode. The brightest spectral lines of this kind were identified as the emission of charged excitonic states (trions) in single InAs/AlGaAs QDs, rather than neutral excitons, as they do not possess any visible linear polarization splitting. These lines possess full width at half maximum about 0.2 meV that is typical for the emission of single-QDs (figure 4). Autocorrelation measurements performed at the excitation power 2–4 times lower than that corresponding to saturation of the QD emission demonstrate the \( g^{(2)} \) function value at zero delay less than 0.2 that clearly confirms the single-photon quantum nature of the emission (figure 5). The estimated count rate of the single-photon emission “at the first lens” exceeds 1 MHz.

Figure 4. Micro-photoluminescence spectrum of a micropillar structure with a submicron lateral size.

Figure 5. The second-order correlation function for the brightest line in the \( \mu \)-PL spectrum shown in figure 4 under both cw and pulse laser excitations.
As compared to the single-photon emission in etched mesa-structures without DBRs, fabrication of the hybrid microcavity results in the intensity enhancement approximately of one order of magnitude. As-grown flat InAs/AlGaAs QDs structures possess sufficiently lower intensity (2 - 5 times weaker than in mesa-structures).

4. Conclusions
We have fabricated micropillar structures with a hybrid semiconductor-dielectric DBR microcavity with low enough InAs/AlGaAs QDs surface density, which are suitable for single-photon applications in the red part of the visible spectral range. The obtained count rate value of the single-photon emission is above 1 MHz with the value of g(2)(0) below 0.2 at non-resonant above-barrier excitation.

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