

Scanning near-field microscopy of microdisk resonator with InP/GaInP quantum dots using cantilever-based probes

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Abstract. We present cantilever-probe based scanning near-field microscopy (SNOM) studies of GaInP microdisks resonators (radii $R=2\text{ }\mu\text{m}$ and quality factors $Q\sim 1000$) with embedded InP quantum dots (QDs) emitting at $\sim 750\text{ nm}$. Near-field photoluminescence spectroscopy in collection regime, using side excitation from micro-objective, was used for imaging of whispering-gallery modes (WGMs) with a spatial resolution below the light diffraction limit. Using collection-illumination regime we imaged the position of single InP/GaInP QDs in microdisk.

Introduction

Using scanning near-field optical microscopy (SNOM) allows to measure optical fields in passive [1,2] and active [3,4] nano-photonic cavity structures with spatial resolution beyond light diffraction limit under optical pumping. While in passive structures the field is excited by external waveguide coupled to the cavity, in active structures the emission of active element is detected. In the last case the effects of interaction of emitting media with cavity modes can be probed [4], which is important for optimization of nano-lasers and single photon sources. So far most of measurements of optical fields in active cavity structures have been performed using tapered fiber metal coated aperture probes [5] or uncoated fiber apertureless probes [2–4]. Recently cantilever-based probes were used for measurements of the field of lasing mode [6] and plasmonic waveguide in stripe laser structures under electrical pumping [7]. In the present paper we used cantilever-probe SNOM for photoluminescence (PL) spectroscopy measurements of GaInP microdisks with InP quantum dots (QDs) embedded. Using collection and collection-illumination regimes we demonstrate using cantilever-probe SNOM to measure optical fields of cavity whispering-gallery modes (WGMs) and location of individual QDs in the cavity.

1. Experimental details

Cantilever-based SNOM setup consists of AFM head with build in 6-mm working distance $100\times$ objective (0.7NA, Mitutoyo), light input-output module connected to AFM base unit (NTEGRA Spectra, NT-MDT) and confocal spectrometer (OMU34, NT-MDT) with a 473nm laser (Cobolt Blues, Cobolt) and a CCD (iDus, Andor Technology) coupled to the AFM system. AFM registration system consists of 1064nm laser which goes through high NA $100\times$ objective and 4-section InGaP photodiode which detects tip-sample interaction. AFM tapping mode applied keep interaction between tip and



surface on the same level and to collect SNOM images. Sample is mounted onto XYZ piezotube scanner with build-in capacitance sensors.

Hollow-pyramid near-field cantilever probe (SNOM_NC, NT-MDT) with aperture size of about 100 nm was used. It has 70° internal angle coated by 100 nm Al layer. Probe is mounted in the AFM tip holder with the tilt angle 11° to sample plane and positioned in the center of high NA objective with the help of viewing microscope. 100 \times objective with 0.7NA collects most of the signal collected by aperture as objective cone angle to the axis is 45°.

Two excitation SNOM configurations were applied: side illumination and illumination-collection through the aperture (figure 1). In side illumination configuration laser beam coupled to optical fiber is focusing to the sample surface by 0.28NA lens. Angle of incidence between beam optical axis and sample plane is equal to 17°. Side illumination optics is positioned on micrometer manual positioner (Newport) allowing bringing laser spot under the hollow-pyramid cantilever. Focused laser spot has 1.7 μm ×5.5 μm dimensions. Taking into account 10mW of laser intensity focused to the sample and 85% power focused into the central Eire spot, an average power density on the sample surface is 1.15mW/ μm^2 . Polarization in the focused laser spot is aligned along X axis.

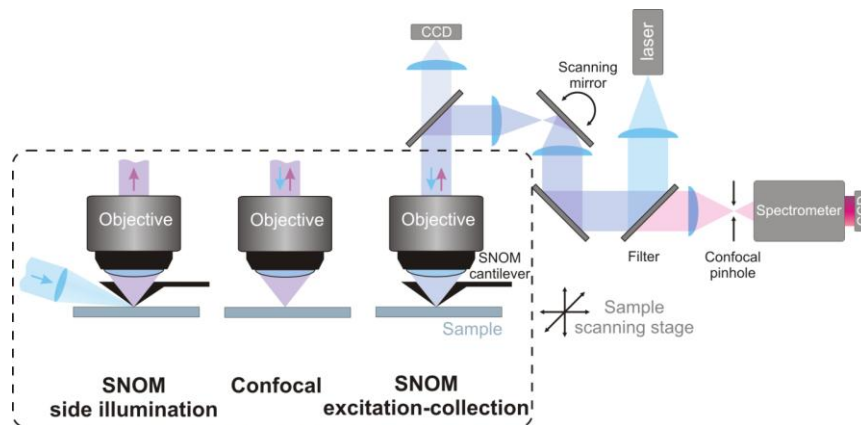


Figure 1. Excitation and collection configurations of setup.

In illumination-collection SNOM configuration 7mW laser is focused to hollow-pyramid apex. Same objective is using to collect luminescence collected through aperture. Precise control of laser beam position is performed by mirror-scanner which build-in into light input-output module. Tightly focused laser spot scans around the aperture by mirror-scanner. Collected light is directed from input-output module to confocal microscope with two 473 nm edge filters (Semrock) and cross slit. In addition confocal upright scheme applied. In this case no SNOM cantilever used. Sample excitation and collection were performed via the same objective with 0.07 mW laser power. Confocal detection scheme allows minimize background signal and therefore improve resolution and SNOM signal/background signal ratio. 520 mm focal length spectrometer equipped by 150 lines/mm grating and 1024 pixel CCD provides spectrum in each point. Acquisition time varies from 0.1 s/point in confocal mode or side illumination SNOM mode to 3 s/point in illumination-collection SNOM mode. Spectrum and data analysis was performed using the image analysis Nova software (NT-MDT).

2. Sample description

Microdisk resonators – were prepared from a 150 nm thick GaInP waveguide structure with embedded self-organized InP quantum dots grown by Metal-Organic Chemical Vapor Deposition (MOCVD). For uncapped structure, used to estimate dot density, the upper part of Ga_{0.52}In_{0.48}P waveguide was not grown. The structures have been grown in a horizontal AIX200/4 reactor under pressure of 100 mbar. Initially a 700 nm thick AlAs layer was deposited on the GaAs wafer. Then a 150 nm thick Ga_{0.52}In_{0.48}P waveguide layer lattice-matched to GaAs was grown with InP QDs at the center. The QDs were grown

at 725 °C by depositing 7 monolayers of InP. Microdisks having $D = 2\ \mu\text{m}$ were fabricated using electron beam lithography (EBL) and inductively-coupled plasma reactive ion etching (ICP-RIE) by using either a wafer bonding (WB). The waveguide was first wafer-bonded to a Si wafer using a spin-on-glass (SOG) precursor (Filmtronics, Inc.) solution, then the GaAs substrate and the AlAs sacrificial layer were removed by mechanical polishing and chemical etching. Finally the MDs were prepared from this structure using EBL and ICP-RIE.

3. Results and discussions

The emission spectrum of the ensemble of QDs, measured in the confocal configuration from an area of about square micrometer, contain broadband peak $\sim 750\ \text{nm}$. To obtain spectra from separate QDs in the near-field configuration, aperture cantilevers with improved transmission ($\sim 10^{-2}$) was selected. The transmission of light by the aperture was measured at the excitation wavelength of 473 nm. Same $3 \times 3\ \mu\text{m}^2$ area was investigated by AFM and SNOM providing an AFM surface topography (figure 2) and the confocal (figure 3) and SNOM (figure 4) luminescence intensity map from InP QDs in the spectral range 750-780 nm. Topography and SNOM image were obtained in tapping mode to avoid any damage to the sample.

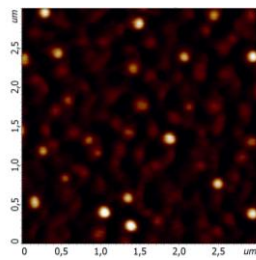


Figure 2. Topography.

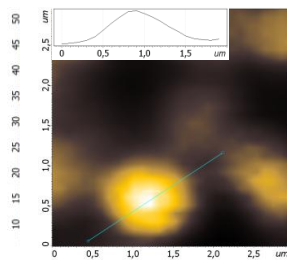


Figure 3. confocal map (750-780 nm).

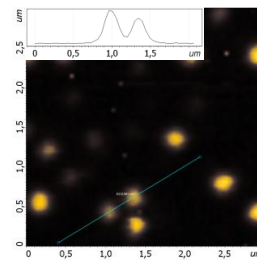


Figure 4. SNOM map (750-780 nm).

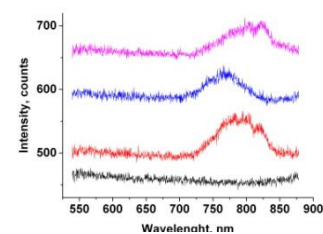


Figure 5. SNOM spectra of QDs and background (bottom).

SNOM photoluminescence was excited through aperture by 473 nm laser and collected by SNOM aperture with 0.5 s exposure time in each point. Spectrum was recorded for each point of the scanning area. It can be seen that individual QDs are resolved in the SNOM luminescence intensity maps. The full width at half-maximum (FWHM) of the optical signal profile taken via individual small QDs is approximately 350 nm (see the inset of figure 4). Using the Rayleigh criterion and taking into account the real sizes of the 200-250 nm emission sources, we obtain for the SNOM with the subwavelength aperture used in the study an estimated resolution of about 100 nm.

Individual QD spectra are clearly resolved and distinguished from each other (figure 5) even for QDs with less than 500 nm distance. The main advantages of near-field spectroscopy through nanoapertures arise from the inherent and absolute stability concerning the arrangement of the aperture relative to the QD. We should pointed out that previously spectra of individual semiconductor QDs were recorded using metalized fiber probes at cryogenic temperatures [8] and there was only one publication on imaging of individual QDs at room temperature [9]

AFM topography of the selected microdisk is shown on the figure 6. Spatial distribution of the luminescence from QDs in the microdisk resonator (figure 7) was obtained in SNOM illumination-collection configuration. It represents a location of individual dots. Spectral distribution of selected QDs in microdisk is presented on the figure 8. It was shown that light emitted from QDs in the central region of resonator is involved in Fabry-Perot mode oscillations only [4]. Whispering-gallery modes appears only when the reflection angle equals to total internal reflection angle and therefore QDs which are located close to the edge are involved into whispering-gallery mode oscillations. Optical pumping of the resonator was performed by side illumination and covers the entire disk area.

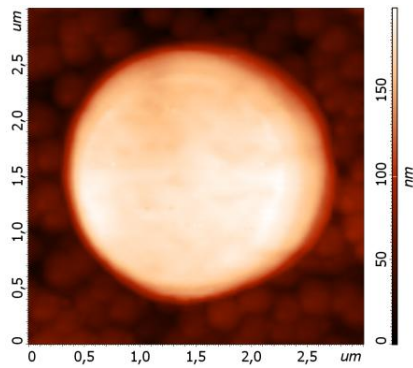


Figure 6. Topography, obtained by SNOM cantilever probe.

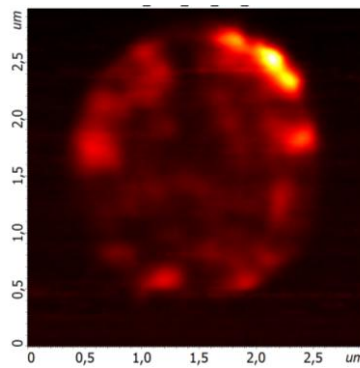


Figure 7. SNOM map (720-730 nm) with 0.5 s per point.

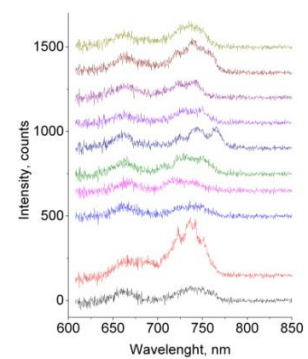


Figure 8. SNOM PL spectra of single QDs in excitation-collection mode.

Figure 9 presents the experimental confocal and SNOM spectrum from microdisk collected from the edge of the disk. Both Fabry-Perot and whispering-gallery modes are detected, but in contrast to confocal detection scheme Fabry-Perot modes are much weaker compare to whispering-galleries modes. Most likely this is due to smaller area from which spectra acquired. SNOM maps of 733.4 nm peak and 755.3 nm peak which corresponds to TE_{20} WGM and TE_{18} WGM respectively are shown on the figure 10 and figure 11.

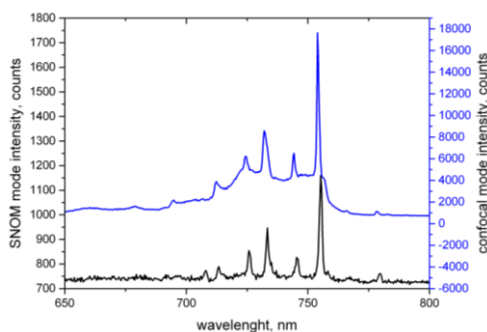


Figure 9. Confocal WGMs (top) and SNOM (bottom) spectra.

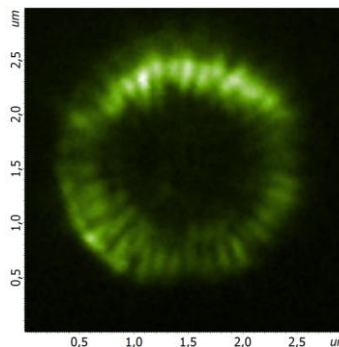


Figure 10. SNOM WGM TE_{20} mode, 732-735 nm.

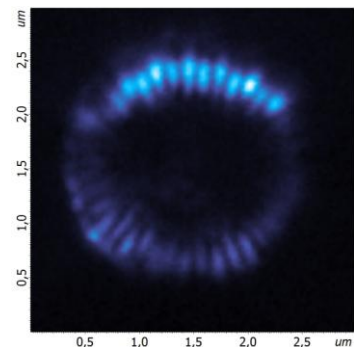


Figure 11. SNOM WGM TE_{18} mode, 753-757 nm.

4. Conclusions

Photoluminescence of self assembled InP/GaInP QDs with the size of 250 nm was studied. Illumination-collection regime of cantilver-based SNOM was used (excitation and emission collection through the same SNOM aperture). Hyperspectral SNOM photoluminescence maps resolving individual QDs were obtained. Luminescence spectra of individual QDs (with emission at 700-780 nm) were measured; spectral difference between single QDs was observed. Corellated images of topography and SNOM photoluminescence were obtained. Both tapping and contact feed back mechanisms were applicable in cantilever based SNOM. Optical resolution of photoluminescence maps was 100 nm, which is about $\lambda/7$.

Configuration with far field side excitation under the SNOM cantilever probe and collection through SNOM aperture was applied to investigate whispering-gallery modes distribution in a microdisk resonator of 2 μm diameter containing InP/GaInP QDs. Distribution of individual QDs in the microdisk resonator was obtained. Fine structure of optical whispering-gallery modes was identified both spectrally and spatially. Q-factor of selected whispering gallery mode was of order of 1000.

Acknowledgement

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