Combined Atomic Force Microscopy and Photoluminescence Imaging to Increase the Yield of Quantum Dot Photonic Devices

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Abstract: We present a combined optical and AFM characterization technique that determines whether single InAs/GaAs quantum dots appear in proximity to (up to micron-sized) topographic surface features that can be detrimental to quantum photonic device performance.

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1. Introduction

Single solid-state quantum emitters are promising ingredients for quantum information protocols relying on the storage, manipulation, and transmission of the information encoded in single photons. Epitaxially grown, self-assembled InAs/GaAs quantum dots (QD) are a particularly promising system, having been used in recent demonstrations of bright, indistinguishable single-photon generation[1-4]. One open question is whether such sources can be created with high yield. We address two challenges in this pursuit, namely, the random spatial location with which self-assembled QDs appear in the plane of the wafer, and the presence of nearby defects that are formed during the growth process and which can adversely affect the QDs and/or photonic devices created around them. In particular, we demonstrate a combined photoluminescence imaging and atomic force microscopy (AFM) approach to identifying QDs that are suitable candidates for use in quantum photonic devices.

2. Discussion of the results

We use photoluminescence imaging as a high-throughput technique to locate single QDs with nanometer scale accuracy[5-7], by imaging their emission, along with reflected light off reference alignment marks, onto a sensitive CCD camera. A schematic of the sample and an example of a photoluminescence image of the QD emission and alignment marks are shown in Figs. 1(a)-(b). We note that wide-field illumination (all QDs within a >50 um x 50 um area are excited) and multiplexed detection enable such an image to be acquired in a 1s long acquisition time, and due to the high signal-to-noise ratio in the obtained image, the QD location with respect to alignment marks can be determined with <5 nm uncertainty[7]. We then combine this optical technique with tapping mode AFM to study the sample's surface in correspondence to the area where the QD had been optically located[8].

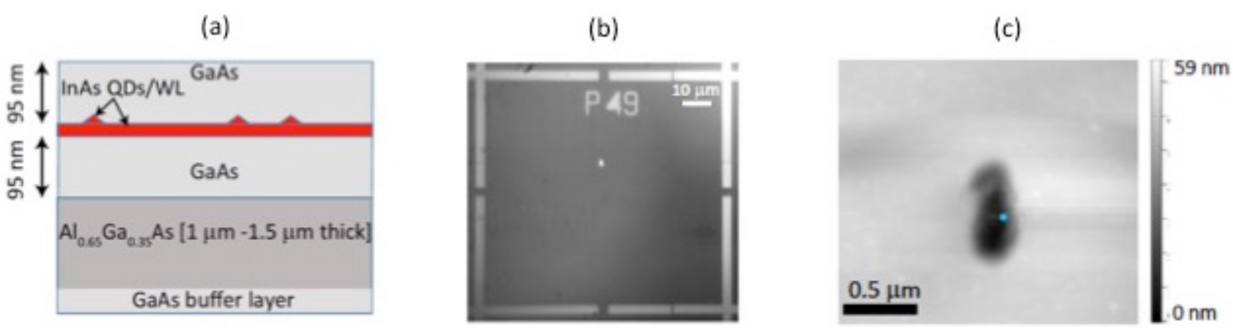

Fig.1: (a) Schematic of the sample under study (not to scale), comprising a single layer of InAs quantum dots (red triangles), grown on an InAs wetting layer (WL) between two 95 nm thick layers of GaAs, and situated on top of a 1 µm or 1.5 µm thick $Al_{0.65}Ga_{0.35}As$ layer on a GaAs buffer layer followed by a GaAs substrate. (b) Electron Multiplied CCD image of the photoluminescence from a QD and reflected light by the alignment marks (metallic crosses), acquired by illuminating the sample simultaneously with both the red and near-infrared LEDs, at a temperature of 4 K. (c) Two-dimensional atomic force microscope images of a "crater-like" surface feature located in proximity to the QD's emitting dipole position obtained from the photoluminescence images. The colored dot represents the QD location, as extracted from the QD photoluminescence image.

When a surface feature is observed, the position of the QD (distance from the center of the alignment marks) extracted from the optical images is marked on the AFM image (Fig. 1(c)). The AFM images show different surface morphology such as oval defect, sharp dips or crater-like features. We find that a significant fraction (20%-60%) of the QDs across multiple samples from different wafers and growth chambers appear in correspondence to relatively large (100 nm to 1000 nm in-plane dimension; 10 nm to 100 nm out-of-plane dimension) surface features[8] (Fig. 2a).

While we generally do not see that such features influence the QD linewidth at the spectral resolution of 0.05 nm set by our grating spectrometer (Fig. 2b), they are large enough to adversely influence the emission properties of fabricated quantum photonic devices, like micro- or nano-cavities, in which single QDs are often embedded. Figure 2(c) shows the results of finite-difference time-domain simulations, in which semi-ellipsoidal defects (similar in size and shape to the defect observed in the AFM in Fig. 1c) are introduced into the circular grating cavity geometry studied in Ref. 3. Even if the QD is precisely located in the optimal position within this device geometry, the morphological defect can significantly degrade the overall device performance, including the fraction of emitted photons that are collected by a lens of a given numerical aperture, and the radiative rate enhancement of the QD. Given that basic photoluminescence with above-band excitation does not reveal differences in the collected spectra (Fig. 2b), our combined technique can increase the fabrication yield by providing the necessary information to select single QDs that avoid surface defects that would likely reduce the performances of quantum photonic devices.

(a)

Sample	No. of QDs analyzed	AFM feature type	No. of matching AFM/QD positions
I	25	oval	7
II	21	dip	5
III	33	crater	19
IV	10	oval	6

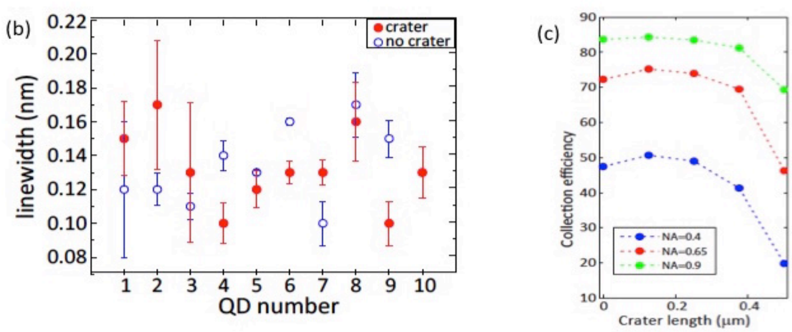

Fig.2: (a) Summary table of the photoluminescence/AFM results obtained from the measurements carried out on the different samples (I, II, III, IV) under study. (b) Linewidths, extracted from Lorentzian fits of single emission lines measured in photoluminescence spectra of QDs found in correspondence to morphological features (filled red symbols) and to smooth surfaces (open blue symbols). The error bars are obtained from one standard deviation uncertainties in the Lorentzian fits. (c) Finite-Difference Time-Domain simulations of the optical properties of a circular grating cavity containing a quantum dot and a crater-like feature close to its center. Collection efficiency of the QD emission into objectives with different numerical aperture (NA), plotted as a function of crater length.

3. Conclusions

We have carried out a study of the surface morphology of GaAs samples containing single QDs and investigated the correlation between surface features and emitter locations. This is made possible by the implementation of a photoluminescence imaging technique that allows us to optically characterize the emitters and find their positions and then to investigate the nearby surface morphology of the sample by means of AFM. By combining photoluminescence and AFM techniques, we are able to correlate the position of the QDs with respect to the surface features observed. Because such surface defects would strongly modify the properties of the photonic devices (e.g., in terms of modal characteristics such as resonant wavelength and cavity quality factor), our technique appears to be important to characterize both the QD's optical properties and the surrounding surface morphology when screening candidate QDs for subsequent incorporation in photonic devices.

4. References

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