Droplet etched $In_xGa_{1-x}As$ quantum dots embedded in $In_{0.52}Al_{0.48}As$ for optical C-band emission

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Semiconductor quantum dots (QDs) have been established as promising sources for on-demand single photon and entangled photon pair generation for quantum communication applications [1]. In the case of polarization entangled photon pairs, it is possible to utilize the biexciton-exciton cascade of a QD system. Here GaAs/$Al_xGa_{1-x}As$ QDs grown via local droplet etching (LDE) have been proven to be the current gold standard, as they exhibit very low fine-structure splitting (fss) due to good in-plane symmetry and their negligible strain [2]. However, for the GaAs/$Al_xGa_{1-x}As$ system one is limited to photon emission around 780 nm. In this contribution, we present the adaptation of the LDE technique to the InP/$In_yAl_{1-y}As$/$In_xGa_{1-x}As$ system for photon emission in the optical C-band. We show that we can produce nanoholes that display very good in-plane symmetry when utilizing optimized process parameters for the etching process. This we could conclude from atomic force microscopy (AFM) measurements. We investigated the influence of the etching material (In, Al, InAl), the etching temperature and the amount of etching material on the resulting nanohole geometry. When In is included in the etching material we found that the nanoholes start to degrade after the As_2 flux is resumed following the etching step (see Fig. 1). We however found that the nanoholes can be conserved by overgrowing them with a thin $In_{0.52}Al_{0.48}As$ layer directly after resuming the As_2 flux. Etching temperatures of T_{etch} = 410 °C and 435 °C proved to be optimum regarding hole depth and in-plane symmetry. Fig. 2 summarized our finding for varying amounts of etching material θ_{InAl} for an exemplary T_{etch} = 435 °C. For larger amounts of etching material, we observe a bi-modal distribution of hole sizes. For θ_{InAl} = 2.7 ML and θ_{InAl} = 1.4 ML only one type of nanoholes is found. The hole depth stays constant at ca. 30 nm but the hole diameter decreases with decreasing θ_{InAl}. Reducing θ_{InAl} to 0.7 ML decreases the hole depth to less than 20 nm and for θ_{InAl} = 0.3 ML no holes at all have been observed. Further experiments have shown that these nanoholes can be filled with $In_xGa_{1-x}As$ and that the filling works better when utilizing an As_4 environment instead of As_2. Finally, we demonstrate that the filled nanoholes emit light when embedded in an $In_{0.52}Al_{0.48}As$ matrix. The emission wavelength can be tuned to the optical C-band by adjusting filling level and In-content (see Fig. 3). µ-photoluminescence spectroscopy reveals sharp emission line typical for individual semiconductor QDs.

[1] S. F. C. da Silva et al., App. Phys. Lett. 119, 120502 (2021).
[2] Y. Li et al., Chinese Physics B 27, 020307 (2018).

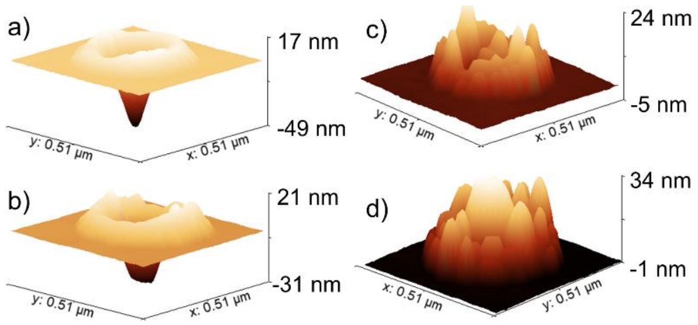

Fig. 1: AFM surface scans of nanoholes produced by In droplet etching after different time lengths of As_2 exposure. After the etching step the As valve was opened for 0 (a)), 1 (b)), 3 (c)) and 5 min (d)) before cooling down the sample at a rate of 30 K/min. Etching on all samples was performed at $p_{As2} = 2 \times 10^{-7}$ mbar with $\theta_{In} = 1.4$ ML and at $T_{etch} = 435$ °C

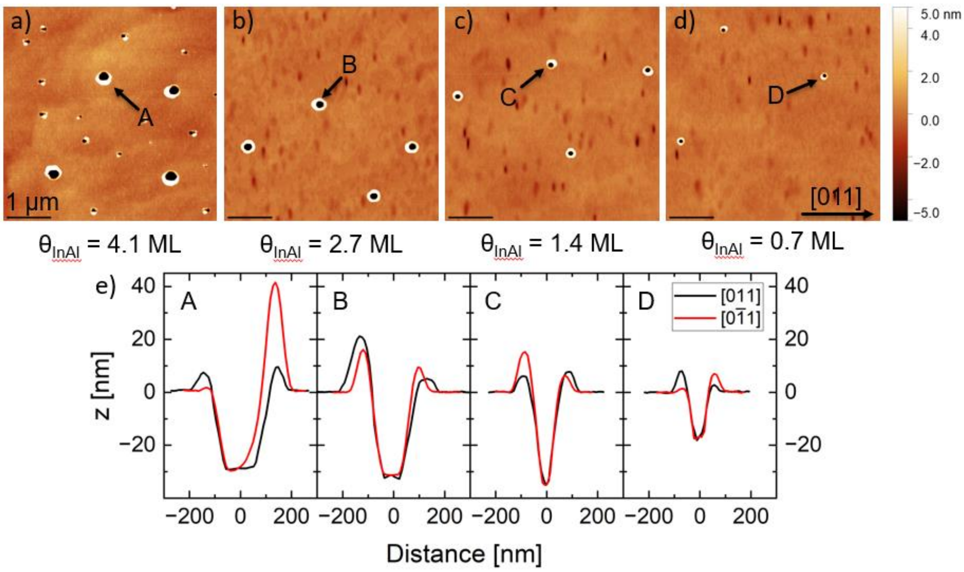

Fig. 2: a) - d) AFM measurement series of samples produced by varying the amount of the etching material (InAl) at a fixed etching temperature of T_{etch} = 435 °C, residual As_2 pressure of $p_{As2} = 2\times10^{-7}$ mbar, annealing time of 3 min and heating the samples to 505 °C after the LDE process. e) Corresponding line scans for the two high-symmetry directions of selected nanoholes indicated in the AFM images. $\theta_{InAl} = 0.3$ ML was tested as well and resulted in a nanohole-free surface.

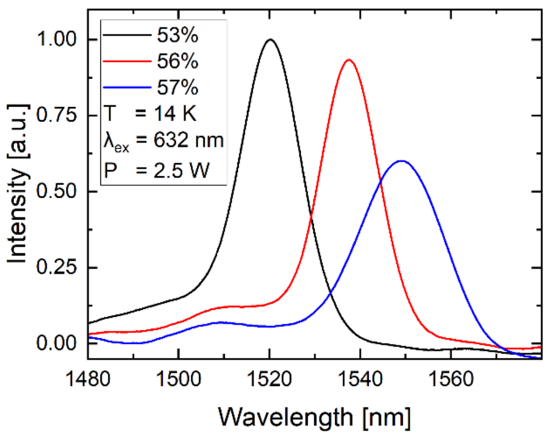

Fig. 3: Ensemble PL spectra of droplet etched $In_xGa_{1-x}As$ QDs embedded in an $In_{0.52}Al_{0.48}As$ matrix. The nanoholes were etched at T_{etch} = 435 °C, with $\theta_{InAl} = 1.4$ ML and $p_{As2} = 2\times10^{-7}$ mbar residual As_2 pressure producing ~33 nm deep holes. These nanoholes were completely filled with $In_xGa_{1-x}As$ and then overgrown with $In_{0.52}Al_{0.48}As$.