

Controlled Synthesis of InGaN Quantum Dots for Efficient Light Emitters

Xiongliang Wei*, Syed Ahmed Al Mueyed, Matthew Peart, Nelson Tansu[‡], and Jonathan J. Wierer, Jr.^{**}

Center for Photonics and Nanoelectronics, Department of Electrical and Computer Engineering, Lehigh University, Bethlehem, PA 18015, USA

*Email: xw314@lehigh.edu, [‡] Email: Tansu@lehigh.edu, **Email: jwierer@lehigh.edu

Abstract: InGaN quantum dots formed by quantum-size controlled photoelectrochemical etching are demonstrated. The QDs are capped with AlGaIn/GaN passivation layers to reduce surface recombination. These QDs are small-sized, <10 nm in diameter, and emit at ~412 nm with a narrow FWHM of 8 nm at 77 K.

A large decrease in efficiency at high operating currents, or efficiency droop, is a well-known problem of InGaIn-based emitters and is primarily caused by non-radiative Auger recombination [1]. One way to overcome Auger recombination is to use quantum dots (QD) instead of the conventionally used quantum wells (QWs) for the light-emitting active layer. Theoretically, QD active layers will have higher spontaneous recombination rates and optical gain, translating into higher efficiencies at high current densities for both LEDs and laser diodes [2]. These theoretical benefits for QDs can only be realized with a high degree of dimensional control and dot density. The widely used Stranski-Krastanov growth to form QDs cannot produce the necessary size control for these theoretical improvements. Recently, quantum-size controlled photoelectrochemical (QSC-PEC) etching has been demonstrated as a controlled synthesis method of QDs [3]. In this method coherent light is used during PEC etching to create photo-generated holes and induce etching of an initial InGaIn layer. As etching proceeds QDs are eventually formed and shrink in size. As the QDs become smaller they eventually stop absorbing the laser light and the etch stops at a precise energy and QD size. To date, QDs formed with this method photoluminescence with narrow full width of half maximum (FWHM) but only at 4 K, most likely because of surface recombination. Here experiments of QSC-PEC formed InGaIn QDs with and AlGaIn/GaN passivation layer are shown. The QDs are formed by first PEC etching a 15 nm thick $\text{In}_x\text{Ga}_{1-x}\text{N}$ ($x \sim 0.11$) layer grown on a GaN/sapphire template using a 405 nm laser. After QD formation AlGaIn/GaN layers are regrown to passivate the surface recombination. These InGaIn QDs emit at ~412 nm with a narrow FWHM of 8 nm at 77 K.

Figure 1 shows the result of a three-dimensional Schrödinger-Poisson simulations, plotting the energy transition of the ground states versus dot radius for a single InGaIn QD with different indium compositions. The shape of the QD is similar to previous reports [4] and is assumed to be hexagonal in the plane, the sidewall angle is 63.4 degrees, the InGaIn QDs are surrounded by GaN, and the “radius” is the distance from the center to the corner of the hexagonal dot along the QD bottom. Both the QD height and radius are varied in the calculations and the height = $(\sqrt{3}/2)$ radius. All the layers are assumed to be defect-free and full strain and polarization charge is used. As the dot size decreases the transition energy increases showing how the QD absorption will eventually stop during etching. Also, at a specific energy one would expect a larger QD for lower indium compositions as the etch terminates. From the plot, one can predict the emission energy one would expect from a particular dot size and indium composition. For example, at an etch energy of 3.06 eV (405 nm) and an indium composition of 15% one should expect a radius of ~5 nm. Of course, the capping layer affects the final results, and simulations with air and AlGaIn/GaN passivation layers are ongoing.

Figure 2 shows an atomic force microscope (AFM) image of QD layer after QSC-PEC etching. Here, a 15 nm thick $\text{In}_x\text{Ga}_{1-x}\text{N}$ QW ($x \sim 0.11$) is etched with 2M H_2SO_4 under a bias of 0.5V for 10 min to roughen the surface and initiate QD formation, and then followed by another 5 min at a bias of 1.3V to complete the QD etch. The etch laser wavelength is 405 nm, it is pulsed with a frequency of 10 kHz and a 5% duty cycle, and the average power density is 100 mW/cm². The AFM shows the final diameter of dots is ~10 nm and the dot height is ~3 nm. The dot density is ~ 10^{11} cm⁻². The dot density is larger and the dot size is smaller than what can be achieved with Stranski-Krastanov growth. These QDs do not exhibit any photoluminescence (PL) at temperatures of 77-300 K, most likely due to surface recombination.

To recover the light emission, AlGaIn/GaN passivation layers are grown on top of the InGaIn QDs using metal-organic chemical-vapor deposition (MOCVD). The 1 nm thick $\text{Al}_{0.42}\text{Ga}_{0.58}\text{N}$ are grown at 700 °C, and the 10 nm thick GaN are grown at 875 °C [5]. The AlGaIn/GaN capping layers are used because they have been shown to prevent out-diffusion of indium during InGaIn QWs growth, and have also demonstrated that the growth temperature cycling reduces the defect density in the InGaIn resulting in higher radiative efficiencies [4]. The intent of the AlGaIn/GaN layers is to not only passivate the InGaIn QDs, but to also improve their radiative efficiency. Fig. 3 shows an AFM image of QDs from Fig. 2 layer with regrown AlGaIn/GaN passivation layers. The sample has surface areas that are relatively flat and smooth, and other areas with pits. Further investigation is required to identify the location and cause of the pitted surface.

Fig. 4 shows PL, using an argon ion laser at 351 nm and 40 mW, of the passivated InGaIn QD sample and an unetched 20 nm thick InGaIn layer from the same wafer. The peak PL of unetched InGaIn is ~425 nm and the fringing is due to Fabry-Perot interference in the underlying GaN. After etching and regrowth the QDs emit at a peak PL of ~412 nm with

a very narrow FWHM of 8 nm at 77 K. The FWHM of the PL signal is comparable to previous results [3]. This blueshift of the QDs from the etch laser wavelength is most likely caused by the additional polarization induced fields from the AlGaIn/GaN capping layer.

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References

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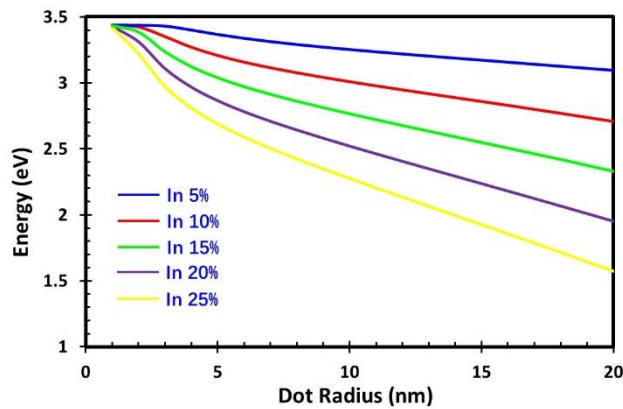


Fig 1: Plot of transition energy of the QD ground states and QD radius for various indium compositions.

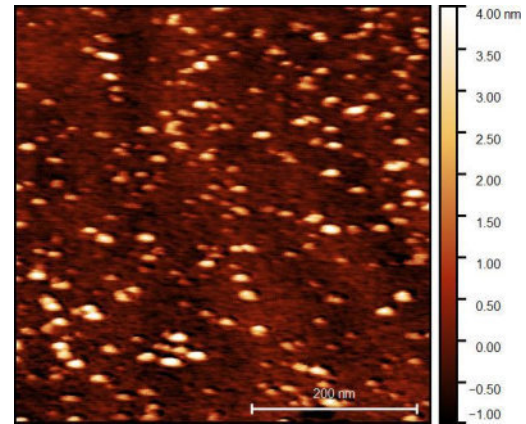


Fig 2: AFM image (500 nm x 500 nm) of InGaIn QDs fabricated by QSC-PEC etching method.

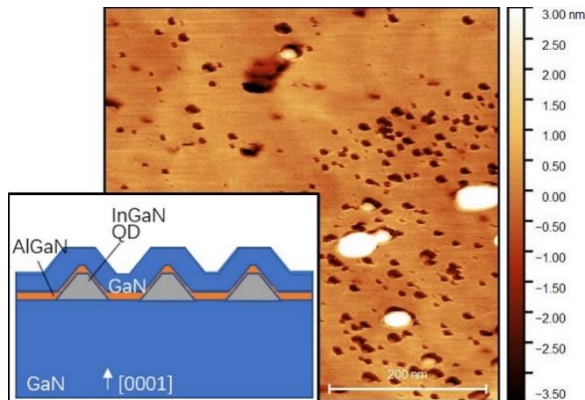


Fig 3: AFM image (500 nm x 500 nm) of InGaIn QD sample with a MOCVD regrown AlGaIn/GaN passivation layers. Inset: Cross-sectional schematic of the structure.

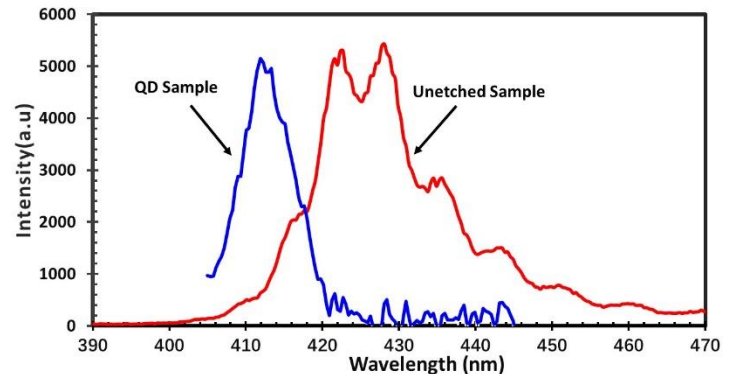


Fig 4: Photoluminescence of an unetched InGaIn sample and regrown InGaIn QD/AlGaIn/GaN sample.