Self-assembled Nitride Quantum Dots for UV Light Emitting Diodes

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The growth and optical properties of $Al_yGa_{1-y}N$ self-assembled nanostructures is investigated and their use as UV emitters in light emitting diodes (LEDs) presented. Taking advantage of a strain induced 2 dimensions (D) - 3D growth mode transition in molecular beam epitaxy (MBE), we have shown the fabrication of nanostructures on $Al_{0.5}Ga_{0.5}N$ using either the (0001) oriented "polar" or the (11-22) oriented "semipolar" surface [1]. Usually, $Al_yGa_{1-y}N$-based nanostructures are grown on AlN surfaces [2]. However, p-type doping, which is a prerequisite for the realization of LEDs, is very challenging for AlN due to the very high acceptor activation energy. Therefore, in our case, $Al_{0.5}Ga_{0.5}N$ materials are used since p-type doping has been shown [3].
UV LEDs are seen as the next technology in replacement to the mercury lamp, but a drop in the efficiency of (Al,Ga)N LEDs for wavelengths < 350 nm is observed. Part of this drop is due to the low structural quality of the active region with typical dislocation densities > 10^9 cm^{-2}. Indeed, higher efficiencies have been shown as a consequence of the $Al_xGa_{1-x}N$ material quality improvement [4].
Our approach is to reduce the influence of defects by confining carriers in 3D in quantum dots (QDs) instead of 1D in quantum wells (QWs). In this work, we investigate the QD growth conditions (deposited amount, composition and/or crystal orientation) on the morphological and optical properties of $Al_yGa_{1-y}N$ QDs grown on $Al_{0.5}Ga_{0.5}N$. The potential of these emitters for UV are discussed and the main characteristics of QD-based LED prototypes presented.
The samples were grown on (0001) c-plane and (1-100) m-plane sapphire substrates. At first, a GaN buffer layer was grown, using MBE for c-plane and Metal Organic Vapor Phase Epitaxy for (11-22) GaN on m-plane sapphire. The structures, grown by MBE in a RIBER 32 reactor, consist of an AlN layer followed by a 1 µm-thick $Al_{0.5}Ga_{0.5}N$ layer (Si-doped for the fabrication of LEDs). The active region is made of GaN or $Al_yGa_{1-y}N$ (with y ~ 0.1) QD planes capped in $Al_{0.5}Ga_{0.5}N$. The $Al_yGa_{1-y}N$ deposited amount to grow the QDs ranges between 1.5 and 2.5 nm. For undoped samples, a final QD layer is grown at the surface and the morphology characterized by Atomic Force Microscopy (AFM). Concerning LEDs, p-type layers are deposited as described in [1]. Undoped samples were characterized by photoluminescence (PL) experiments using a frequency-doubled Ar laser at 244 nm and/or a mode-locked frequency-tripled titanium-sapphire laser with a 2 ps pulse width and a wavelength of 260 nm. LEDs were processed as presented in [1]. Electroluminescence (EL) measurements have been performed on wafer at room temperature in continuous wave conditions.
The QD shape and spatial distribution measured by AFM are presented in Figure 1. In the (0001) orientation, the QDs present an isotropic shape, with lateral sizes of 15 to 25 nm and heights of 2 to 4 nm. In the (11-22) case, chains of QDs are observed, with an elongation and ordering along the <1-100> axis. Their lateral sizes are around 20 and 40 nm and heights around 2 to 3 nm. High QD densities, in the 10^{11} cm^{-2} range, are obtained. The PL properties measured at room temperature are presented in figure 2 for GaN and $Al_yGa_{1-y}N$ (0001) QDs and GaN (11-22) QDs. A blue-shift is observed for $Al_yGa_{1-y}N$ QDs compared to GaN QDs, going from ~ 3-3.2 eV to ~3.6-3.8 eV. In comparison, PL peaks ~ 3.65-3.75 eV are observed for (11-22) QDs. Depending on the QD growth process, these blue-shifts account for one or several contributions: an increase of the bandgap energy, a size reduction and/or the reduction of the internal electric field (F) [1]. Next, GaN QD-based LEDs were fabricated on both (0001) and (11-22) orientations. Current-Voltage and EL characteristics are presented in Figure 3. Rectification behaviour is found in both cases and an EL emission in the UV range, at ~375 nm and ~328 nm is obtained for polar and semipolar QDs, respectively. These results clearly evidence the potential of the $Al_yGa_{1-y}N$ / $Al_{0.5}Ga_{0.5}N$ QD system for UV emission. The shortest wavelength for semipolar LEDs is the consequence of the strong reduction in F.
This work is supported by ANR Project <ANR-14-CE26-0025-01> "NANOGANUV".

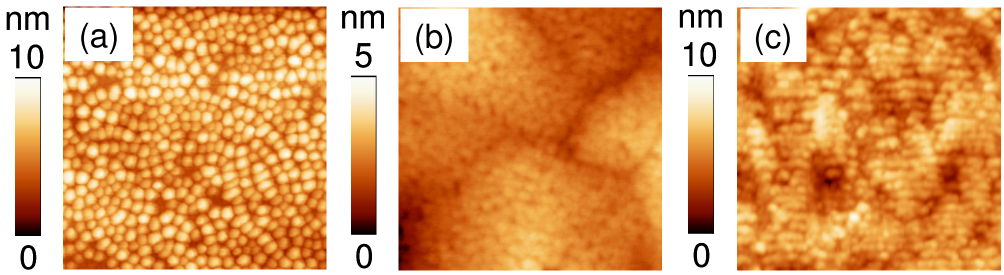

Figure 1 Atomic force microscopy (AFM) images (500x500 nm^2) of : (a) GaN quantum dots (QDs) and (b) $Al_yGa_{1-y}N$ QDs grown on $Al_{0.5}Ga_{0.5}N$ (0001). (c) AFM image of GaN "semipolar" quantum dots grown on $Al_{0.5}Ga_{0.5}N$ (11-22). The quantum dots are aligned along the <1-100> axis.

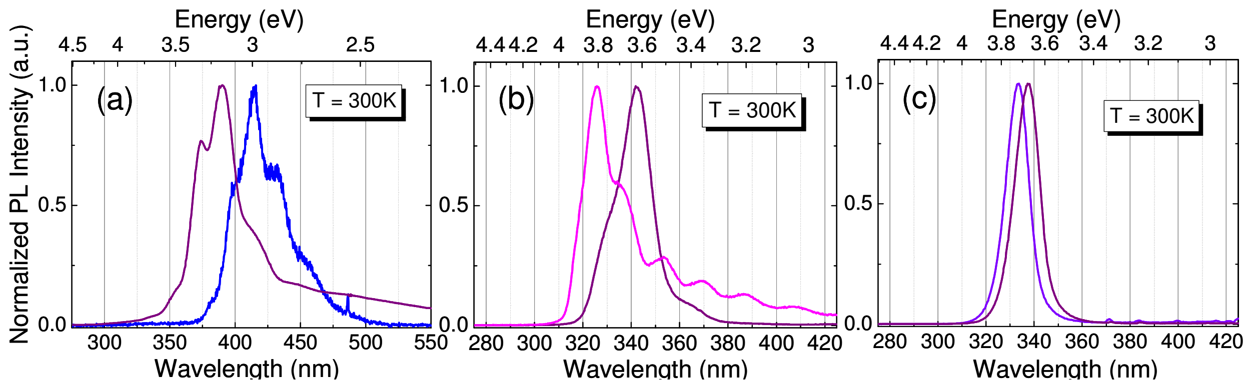

Figure 2 Room temperature photoluminescence spectra of: (a) GaN (0001) quantum dots (QDs), (b) $Al_yGa_{1-y}N$ (0001) QDs and (c) GaN (11-22) QDs grown on $Al_{0.5}Ga_{0.5}N$. In each case, two structures, made with different deposited amounts of GaN or $Al_yGa_{1-y}N$ to grow the QDs, have been characterized.

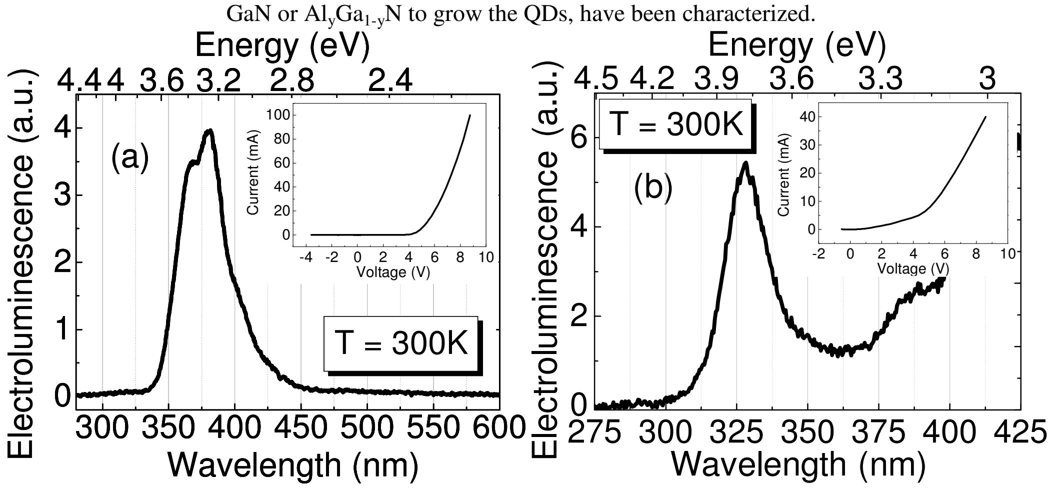

Figure 3 Electroluminescence spectra of (a) GaN (0001) and (b) GaN (11-22) QD-LEDs for injected current values of 20 mA and 60 mA, respectively. The inset in each figure presents the I-V characteristic.

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