Microstructural characterisation of a prototype layer structure for a GaN-based photonic crystal cavity

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Abstract A semiconductor multilayer consisting of an n-type GaN/sapphire pseudo-substrate with a double sacrificial layer (20 nm of InGaN and 20 nm of InAlN) and a GaN cavity structure on top incorporating an InGaN quantum dot active layer was grown. Atomic force microscopy (AFM) was used to measure the morphology of the upper surface of each layer of similar test structures and to assess the morphological evolution of the full structure during its growth. Transmission electron microscopy (TEM) was also used to assess defect incorporation into the structure. AFM showed that the incorporation of a double sacrificial layer was observed to have no detrimental affect on either the formation of the quantum dots, or the morphology of the top GaN capping layer. TEM highlighted the occurrence of threading dislocations propagating through the sacrificial layers into the capping GaN layer, but did not resolve the occurrence of defect generation in the sacrificial layers.

1. Introduction
The group III nitride alloys provide a wide range of possible direct band-gaps making them an ideal choice for optical device applications. These materials are of particular interest in the context of single-photon sources (SPS). Current research into practical device formation for SPS has considered the use of two-dimensional photonic crystal (PC) designs with the hope of obtaining low volume, high quality factor ($Q$) cavities that can significantly enhance emission rates while retaining reliable single photon differentiation; simultaneously providing a versatile template for electronic integration [1]. However, little work has been performed on the nitride semiconductor system in this context, despite the potential advantages these materials offer over the more conventional arsenides in terms of available wavelengths, wavelength tunability and temperature stability of single photon emission [2].

Despite being ideal sources, the three-dimensionality of quantum dots (QDs) poses a difficulty for efficient photon extraction, as emission is probable in all directions. Furthermore epitaxial QDs form as embedded islands on, or within, a semiconductor matrix and therefore suffer from a high surrounding refractive index ($n$). As well as the surrounding strong photon refraction, the spontaneous emission lifetime within the QD is deeply related to the dipole moments of the immediate environment. QDs therefore need to be coupled with an optical cavity in such a way that can enhance the rate of spontaneous emission (by a quantity known as the Purcell factor, $f_P$ [3]) while collecting and channelling the emitted photons into identical spatial modes [4]. The formation of high $Q$ cavities with small modal volumes is therefore a key step in achieving a functional SPS. Recent published work on two dimensional PC membrane cavities have reported $V_{eff}$ values down to $\sim0.7(\lambda/n)^3$ and large
$Q$ factors of the order of two million [5], with a potential theoretical increase to $>10^7$ with further optimization [6].

Fundamentally, the efficiency of a PC system depends on the quality of its internal and surface structure. The presence of internal structural defects and surface roughness disrupt the photonic band-gap incurred by the structures periodicity, and can severely degrade the $Q$ of a promising design. One of the main priorities during fabrication is therefore in developing methods that can minimise the occurrence of structural defects, and ensure that surface roughness is kept to a minimum. The use of epitaxial deposition techniques (such as metalorganic vapour phase epitaxy – MOVPE) already prevents, to some extent, the scale of imperfections that would occur through other growth methods, as well as being vital to the formation of high quality QDs. The main source of imperfections therefore occurs during post-processing of epitaxial grown structures. One method of reducing defect formation during post-processing is by including sacrificial layers that react more vigorously with selective etchants compared to the rest of the structure. This allows for a ‘clean’ cleavage of the intended optical area from the rest of the structure, with minimal handling, and is clearly advantageous in comparison to other dry/wet etching methods. Such a process may be carried out through a photo-electrochemical (PEC) etch [7], in which a cathode is attached to an n-doped layer below the sacrificial layers and a light source with a wavelength corresponding to the sacrificial layers band-gap is directed upon them. The generation of a large concentration of holes in the sacrificial layers resulting from the abovementioned process promotes a higher etching rate, and can be tuned to selectively target other layers with differing band-gaps.

What naturally remains to be determined is what effect the inclusion of the sacrificial layer(s) has on the propagation of and/or generation of defects throughout the cavity and the roughness of interfaces within the structure. In this paper we have assessed and compared the surface morphology of the various layers by atomic force microscopy (AFM). Preliminary transmission electron microscopy has also been carried out in order assess defect propagation throughout the structure.

![Figure 1](image_url)  
**Figure 1.** Epitaxial multilayer design used for intended photonic crystal cavity formation (not to scale).

### 2. Experimental

All samples were grown through MOVPE in a 6 x 2” Thomas Swan reactor close-coupled showerhead reactor, using trimethylgallium (TMG), trimethylindium (TMI) and ammonia (NH$_3$) as precursors. A SiH$_4$ flux was employed as a source of n-doping and H$_2$ was used as carrier gas for the growth of GaN unless otherwise stated, whilst N$_2$ was used as a carrier gas for all indium-containing layers. The complete structure involved the deposition of 6 layers on an n-doped GaN pseudo-substrate. A schematic of the grown multilayer is shown in Figure 1. Six other incomplete structures were grown to allow assessment of the morphology of the top surface of each of the layers shown in the figure 1 (apart from the pseudo-substrate). Two additional control samples were grown in order to compare and assess how the underlying sacrificial layers affected the growth of the QDs and the surface morphology of the final capping layer. These consisted of two samples of InGaN QDs on a GaN pseudo-substrate one of which was capped with ~10 nm of GaN. Surface morphologies were imaged using a Veeco Dimension 3100 atomic force microscope (AFM) in TappingMode™. Defect propagation throughout the epitaxial structure was probed with the use of a Philips CM30 transmission...
3. Results and Discussion

3.1. AFM Characterisation

Surface morphologies were mapped and compared using AFM to scan the surfaces of each of the partial multilayers. The first layer to be grown was a ~500 nm n-doped (~1 x 10¹⁹ cm⁻³) GaN connecting layer, the purpose of which was to cover the re-growth interface and provide a clean and flat surface for subsequent growth, as well as to provide an electrical connecting layer for a cathode necessary in the PEC etch process. Figure 2(ai) and 2(aii) show the surface morphology of the GaN pseudo-substrate with a terraced surface and a root mean square roughness ($R_q$) value of 0.69 nm over a 5 µm × 5 µm area. The subsequent growth of a double sacrificial layer above the n-doped GaN could potentially affect the morphology of the subsequent GaN layer, and thereby affecting the growth of the QD layer. 20 nm of In₀.₀₆Ga₀.₉₄N and 20 nm of In₀.₁₇₅Al₀.₈₂₅N were grown to provide the main sacrificial breaking point for the separation of the top three layers from the rest of the structure. These materials were chosen since they are expected to experience high etch rates in the PEC process. Figures 2(bi,bii) and 2(ci,cii) show the surface morphology of both the sacrificial layers, and figure 2(di,dii) shows the surface morphology of the subsequently deposited GaN layer to be very similar to that of the underlying GaN, with an $R_q$ value of ~0.39 nm for a 5 µm × 5 µm area. The final three layers constituted the intended PC membrane and consist of a monolayer of In₀.₂Ga₀.₈N QDs sandwiched in-between two ~60 nm GaN layers. The final capping GaN layer shown in figure 2(fi,fii)
shows considerable surface roughness ($R_q \approx 1.73$ nm over $5 \mu m \times 5 \mu m$), an effect which probably occurs since the final GaN cap was grown in N$_2$ to avoid exposing the QD layer (ei,eii) to an H$_2$ flux which might alter its properties.

The AFM scans of the control samples are show in Figure 3 and are similar to the corresponding QD and capped QD layer scans in Figure 2, with the capped QDs sample (figure 3(bi,ii)) having a slightly lower $R_q$ value of $\approx 1.26$ nm over a $5 \mu m \times 5 \mu m$ area.

3.2. TEM characterisation

Preliminary TEM images were taken along the (01 $\overline{T}$0) axis and two such micrographs are shown in figure 4. Although the stacked layers can be distinguished, the effect of the sacrificial layers on the GaN sandwiched QD layer is not observable. Threading dislocations can be seen propagating from the underlying n-type GaN through the sacrificial layers and the cavity structure in figure 4(a). However, no defect generation in the sacrificial layers is visible in these images. More detailed TEM characterisation will be required in order to check whether such defect generation occurs.

4. Conclusions

AFM scans of the various partial stacks show no significant deviations from similar morphology scans reported in the literature [8] [9]. With exception of the capping GaN layer, the various layers are observed to possess relatively smooth surfaces and the sacrificial layers are not observed to detrimentally affect the formation of the QDs. The preliminary TEM characterisation highlighted the occurrence of threading dislocations propagating through the sacrificial layers into the capping GaN layer. As the obtained TEM data was in no way conclusive, further studies will be carried out in order to clarify the roughness and abruptness of the various interfaces, as well as to more thoroughly assess defect incorporation throughout the stack and the influence of the sacrificial layers on the defect formation in the top GaN layers. Additionally, the effectiveness of PEC etching for the current sacrificial layers must still be assessed.

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