Strain Relief InGaN/GaN MQW Micro-pillars for High Brightness LEDs

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***Abstract*—Micro-structured group-III-nitrides are considered as promising strain relief structures for high efficiency solid state lighting. In this work, the strain field in InGaN/GaN multi-quantum wells (MQWs) micro-pillars is investigated using micro-Raman spectroscopy and the design of micro-pillars were studied experimentally. We distinguished the strained and strain-relieved signatures of the GaN layer from the E_2 phonon peak split from the Raman scattering signatures at 572 cm^{-1} and 568 cm^{-1}, respectively. The extent of strain relief is examined considering the height and size of micro-pillars fabricated using focused ion beam (FIB) micro-machining technique. A significant strain relief can be achieved when one micro-machined through the entire epi-layers, 3 μm in our study. The dependence of strain relief on micro-pillar diameter (D) suggested that micro-pillar with $D < 3$ μm showed high degree of strain relief. Our results shed new insights into designing strain-relieved InGaN/GaN microstructures for high brightness light emitting diode arrays.**

Keywords— InGaN/GaN quantum well; micro-pillar; strain relief.

I. INTRODUCTION

InGaN/GaN based light-emitting diodes (LEDs) are promising energy saving candidates for solid state lighting applications [1]. However, its internal quantum efficiency suffers from a “droop” when operating under high power, in which the efficiency reaches its peak value at low current density and rapidly decreases with increasing injection current [2]. The piezoelectric polarization caused by residual strain in epi-layers during the cooling process in a growth chamber is one of the main reasons [3]. The hexagonal crystal structure and disparate lattice-mismatch between LED epitaxy and sapphire substrates further aggravate the situation. This work involved post-growth epitaxy strain engineering by fabricating micro-structures on the multiple quantum wells (MQW) based LED epitaxy. It is also worth mentioning that micro-structuring InGaN/GaN MQWs brings benefit on the external quantum efficiency because of an improved light escape design based, which is limited by total internal reflection (TIR) in large-area LED structures. With proper heat sinking design, the eventual high wall-plug efficiency may potentially lead to realization of high brightness LEDs beyond >200 lumens per watt for general illumination. Furthermore, the micro-structured LED pillars in the form of an array has low the RC constant, which can be potentially used in visible light communication, such as the Light Fidelity (Li-Fi) concept, which is capable of transmitting data at a high speed of 100 – 500 MB/s [4].

Current work based on micro-photoluminescence (μPL) in pillars [5] and strips [6] revealed strain relief but failed to obtain detailed mechanism and strain distribution due to limited spatial resolution. Besides, the fabrication parameters, such as the height and size of pillar were chosen randomly, and hence the studies were lacking in terms of a systemic study for designing low strain structures targeting eventual general illumination or data communication implementation. In our work, the residual strain and relieved strain the in micro-pillars were examined by micro-Raman scattering spectroscopy (μRaman). A systemic evaluation of pillar height and size were carried out providing design rules for eventual large scale manufacturing of strain released high brightness LEDs based on, for example, inductively coupled plasma (ICP) etching.

II. EXPERIMENTS

The 12-stack 3*nm*-InGaN-well / 10*nm*-GaN-barrier multiple quantum well (MQW) layer structure was grown on c-plane sapphire using metal-organic chemical vapor deposition (MOCVD). A ~100 *nm* thin layer of indium tin oxide (ITO) was deposited at the top of the epitaxy using radio frequency (RF) sputtering. Micro-structures were fabricated using focused ion beam (FIB) technique in a FEI Quanta 3D dual beam system. μRaman signals were measured in a back-scattered geometry at room temperature using the Horiba HR800 system utilizing 473 *nm*, 532 *nm*, 660 *nm* and 785 *nm* lasers. All the Raman spectra were collected using 532 *nm* laser if not mentioned in the figures. The GaN Raman (strain) signal can be measured at a sufficiently strong intensity level as compare to the thin InGaN QW layer, and hence measuring the GaN Raman signal provides a valid and accurate strain relief measurement. Furthermore, as both GaN and InGaN are having similar thermal mismatch, and both are compressively strain along the growth direction with respect to sappire substrate, one can then infer that the relieve in the GaN barrier strain will result in strain relieve in InGaN well layer in the absence of or reduction in lateral strain in a pillar structure.

III. RESULTS AND DISCUSSION

In this experimental investigation, a series of micro-pillars were fabricated with a large gap (> 10 μm) between any two pillars to ensure that each pillar can be independently measured. µRaman spectroscopy provides a direct measurement of strain field in GaN based epitaxy structures according to the crystal symmetry related formalism [7],

$$\Delta\nu_{E2} = a_{E2}(\sigma_{xx} + \sigma_{yy}) + b_{E2}\sigma_{zz} \pm c_{E2}\sqrt{(\sigma_{xx} - \sigma_{yy})^2 - 4(\sigma_{xy})^2} \quad (1)$$

where σ_{ij} is the stress tensor in the *Wurtzite* crystal basis and *a*, *b* and *c* are the stress-related deformation potentials.

Considering the shear component c is reported to be weak (< 0.3 cm^{-1}/GPa) and assuming in-plain strain in GaN, $\sigma_{zz} = 0$, the formula can be simplified as:

$$\Delta\nu_{E2} = a_{E2}(\sigma_{xx} + \sigma_{yy}) \quad (2)$$

With the strain-free Raman shift of E_2 phonon peak in GaN taken as 567.25 cm^{-1}, the strain field can be examined based on the wavenumber shift of E_2 phonon. After the formation of micro-pillars, we found a peak split in E_2 phonon signature (see Fig. 1). The main peak at 568 cm^{-1} indicates a strain relief up to -0.4 *GPa* in the structure. The existence of a second peak at 572 cm^{-1} is attributed to residual strain.

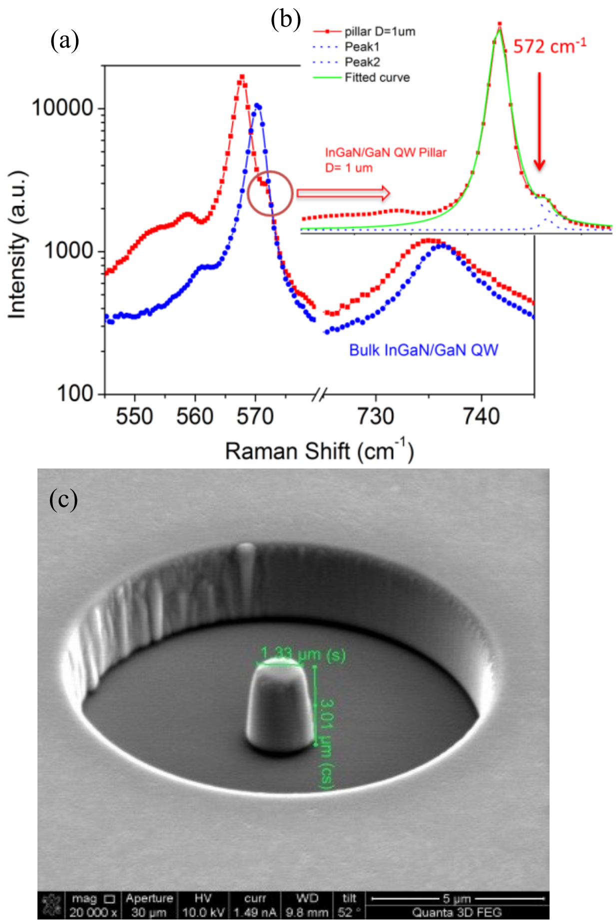

Fig. 1. (a) Raman spectra of bulk InGaN/GaN MQW (blue), and micro-pillars (red); (b) a detailed Raman spectrum showing E2 peak of a 1 μm diameter (D = 1 μm) InGaN/GaN MQW micro-pillar; (c) SEM image of the micro-pillar in (b).

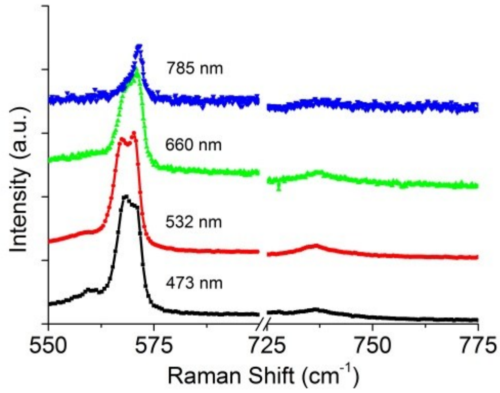

Fig. 2. Raman spectra of an InGaN/GaN MQW micro-pillar measured when independently irradiated with four different laser sources.

Several reasons lead us to this conclusion. Firstly, when micro-machined down to the bottom of the epitaxy, only single peak at 572 cm^{-1} is found. There was no peak splitting or downshifting was measured. Secondly, a power dependent measurement showed no difference in peak positions and intensity ratio, and hence the emerging second peak may not come from micro-machining damage. Finally, we measured the depth dependent Raman spectra using four laser sources. Benefiting from the difference in penetration depth, which is short for 473 *nm* laser and long for 785 *nm*, the strain behavior can be further understood (see Fig. 2). It was found that strain-relief related Raman peak dominated *E2* phonon in Raman spectrum from 473 *nm* excitation source. When the excitation laser wavelength was increased to 785 *nm*, residual strain related peak became dominant. Therefore, the residual strain came from the bottom of the epi-layers, which means the grain layer in this case.

Based on the strain profile characterized by Raman analysis, we further investigated the designing of InGaN/GaN QW micro-pillar for high degree of strain relief as well as low ratio of residual strain. Two major factors were involved in our study- the height of pillar and the size of it.

A. Height of Micro-pillars

While designing the strain-relieved micro pillars, the micro-machining depths or micro-pillar heights (*L*) are considered. Micro-pillars with heights ranging from 460 *nm* to 3.01 μm were studied (see Fig. 3). At L = 462 *nm*, the depth reached the top of active region, while at L = 710 *nm* the depth reached the bottom of MQW region. Within L = 998 *nm* to 2.5 μm, the n-GaN region is exposed. Finally, the whole pillar consists of the entire epitaxy, exposing the sapphire at the surrounding at L = 3.01 μm. Maximum strain relief was found in pillars with depth of 3 μm.

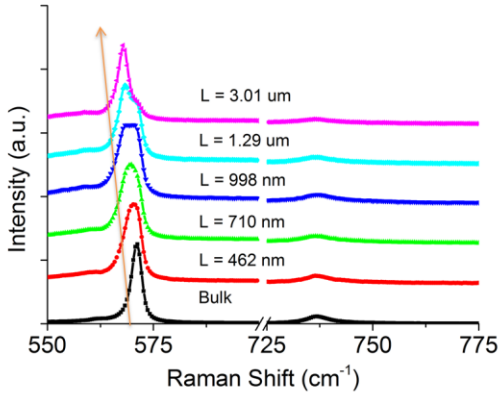

Fig. 3. Raman spectra from bulk LED epitaxy and micro-pillars with different micro-machining depth.

B. *Size of Micro-pillars*

A series of FIB micro-machined pillars were designed to determine the degree of strain relief with respect to pillar size or diameter, ranging from 15 μm to 1 μm. With all Raman signals collected at the center of the pillars, we found a significant strain relief from -1.25 *GPa* to -0.4 *GPa* measured for pillars with diameter smaller than 10 μm (see Fig. 4). It was noted that the strain relief region become the dominant only when *D* was further reduced to 3 μm or less.

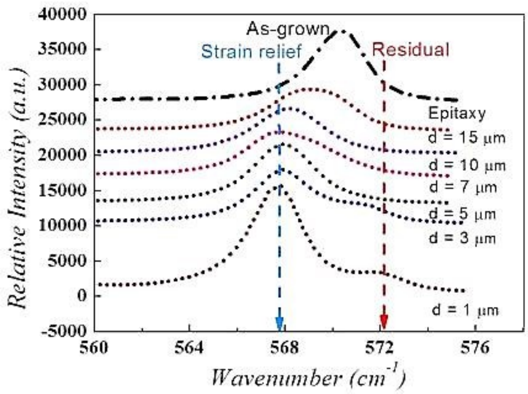

Fig. 4. Raman spectra from micro-pillars with different sizes.

IV. CONCLUSIONS

The strain field in InGaN/GaN MQWs on sapphire was analyzed by µRaman spectroscopy. Our experimental study suggested that micro-pillars with diameter < 3 μm and depth (height) > 3 μm are promising candidates for GaN based high-brightness LEDs.

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