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# Carrier density analysis in stressed n-doped GaN layers on sapphire

Ndembi Ignoumba-Ignoumba<sup>1</sup>, Camille Sonnevile<sup>1</sup>, Eric Frayssinet<sup>2</sup>, Adrien Bidaud<sup>3</sup>, Florian Bartoli<sup>2</sup>, Yvon Cordier<sup>2</sup>, Farid Medjdoub<sup>3</sup>, Dominique Planson<sup>1</sup>, Cyril Buttay<sup>1</sup>

**Abstract**—Using micro-Raman spectroscopy on MOCVD slightly n-doped GaN on sapphire structures ( $1.5 \times 10^{15} \text{ cm}^{-3}$  –  $6.5 \times 10^{15} \text{ cm}^{-3}$ ), we report a method to dissociate biaxial stress contribution from n carrier concentration contribution in  $A_1(\text{LO})$  Raman peak position. For all characterized samples, the main Raman peaks  $A_1(\text{LO})$  and  $E_2^{\text{H}}$  exhibit a linear dependency with a slope of  $\sim 1$  due to biaxial stress and the intercept of the linear regression increases as n carrier density locally increases.

## I. INTRODUCTION

Thanks to GaN's physical properties, GaN-based power devices are very promising. In fact, GaN-based HEMTs using lateral current flow are already commercialized by some companies such as EPC, GaN Systems, STmicroelectronics and Transform. However, vertical structures are more desirable as they allow to reach higher voltages and higher current densities than lateral structure [1]. Our work is part of the VERTIGO PEPR project, which is aimed at producing high-power vertical GaN-based transistors grown on 200 mm diameter silicon substrates demonstrating a BV > 1.2 kV and a current of 50 A. To achieve these goals, optimization of the material quality of the active layer is needed in terms of its mechanical stress, density of defects and n carrier density and homogeneity.

It is well known that the main GaN Raman peaks  $E_2^{\text{H}}$  and  $A_1(\text{LO})$  energy shift under stress [2] while the  $A_1(\text{LO})$  peak is always coupled to the n carrier density [3]. However, we have not yet come across a study of n carrier density considering the effects of non-negligible internal stress variation. Here, we report a method to discriminate between the internal stress contribution and the n carrier density contribution in the shift of the  $A_1(\text{LO})$  peak position, enabling a better evaluation of n carrier homogeneity.

## II. EXPERIMENTS

The GaN epitaxial layers are grown by Metal Organic Chemical Vapor Deposition (MOCVD) at temperatures ranging from 947° C to 1035° C, on 2-inch sapphire substrates. All samples are made of an unintentionally doped GaN layer (nid GaN) used as a buffer layer, a highly Si n-doped GaN layers stack ( $n^+$  GaN  $\sim 5 \times 10^{18} - 10^{19} \text{ cm}^{-3}$ ) to serve as a metal contact layer and a lightly Si-doped active layer (n- GaN). A schematic

view of the samples structure is presented in Fig. 1a. The doping concentrations of n- GaN layers are measured by mercury probe capacitance-voltage (C-V) technique. Micro-Raman spectroscopy is carried out for n- GaN layers, at room temperature, using a confocal spectrometer (Renishaw Invia model) in back scattering geometry with an excitation laser at 532 nm. In addition, n- GaN layers are etched using  $\text{Cl}_2$  and argon dry etching technique (see Fig. 1b), in order to produce semi-vertical Schottky diodes that will serve in the future for electrical characterizations.

The micro-Raman characterizations are done along lines (1 dimensional-1D-scans) before etching and on defined areas (2D scans). For the 1D characterizations, a spectrum is acquired each 10  $\mu\text{m}$  over lines of 6 mm to  $\sim 35$  mm long and curve fittings are performed for the  $E_2^{\text{H}}$  and  $A_1(\text{LO})$  peaks for each spectrum. 8 samples with n-concentration ranging from  $1.5 \times 10^{15} \text{ cm}^{-3}$  to  $6.5 \times 10^{15} \text{ cm}^{-3}$  are analyzed with 3 to 11 lines per sample. For the 2D characterizations, a spectrum is also acquired with steps of 2  $\mu\text{m}$ -4  $\mu\text{m}$  for characterized areas of 80  $\mu\text{m}^2$ -308  $\mu\text{m}^2$ . The same peak fittings are performed for each acquired spectrum.

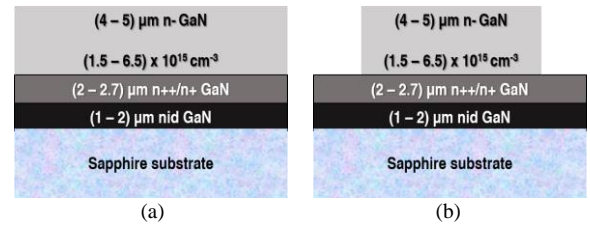


Fig. 1. Schematic view of samples before (a) and after etching (b).

## III. RESULTS AND DISCUSSION

The shift of  $E_2^{\text{H}}$  peak position ( $\Delta\omega_{E_2^{\text{H}}}^B$ ) is mainly due to biaxial stress ( $\Delta\sigma_B$ ) and it is given by Equation (1) [2].

$$\Delta\omega_{E_2^{\text{H}}}^B = \omega_{E_2^{\text{H}}} - \omega_{E_2^{\text{H}}}^0 = K_{E_2^{\text{H}}}^B \Delta\sigma_B. \quad (1)$$

Where  $K_{E_2^{\text{H}}}^B$  ( $\text{cm}^{-1}/\text{GPa}$ ) is the biaxial stress coefficient associated to the  $E_2^{\text{H}}$  peak and  $\omega_{E_2^{\text{H}}}^0$  is the  $E_2^{\text{H}}$  peak position without biaxial stress. As for  $A_1(\text{LO})$ , its shift ( $\Delta\omega_{A_1(\text{LO})}^B$ ) is due to the biaxial stress ( $\Delta\sigma_B$ ) [2] and it is also linearly dependent on the n carrier density ( $\Delta C$ ) [4], for GaN on GaN biaxial stress-free samples

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and  $\Delta C$  lower than  $10^{17} \text{ cm}^{-3}$  [4]. Combining these two effects, the  $\Delta\omega_{A_1(LO)}$  can be expressed with the following equation:

$$\Delta\omega_{A_1(LO)} = \omega_{A_1} - \omega_{A_1}^0 = K_{A_1}^B \Delta\sigma_B + K_{A_1}^C \Delta C. \quad (2)$$

Where  $K_{A_1}^B$  ( $\text{cm}^{-1}/\text{GPa}$ ) is the biaxial stress coefficient associated to the  $A_1(LO)$  peak,  $K_{A_1}^C$  ( $\text{cm}^{-1}/\text{cm}^{-3}$ ) is the concentration coefficient associated to the  $A_1(LO)$  peak and  $\omega_{A_1}^0$  is the  $A_1(LO)$  peak position of a biaxial stress-free undoped GaN layer. Combining  $\Delta\omega_{E_2^H}$  and  $\Delta\omega_{A_1(LO)}$ , we obtain the  $A_1(LO)$  peak position ( $\omega_{A_1(LO)}$ ) as:

$$\omega_{A_1(LO)} = \frac{K_{A_1}^B}{K_{E_2}^B} \omega_{E_2} + K_{A_1}^C \Delta C + \omega_{A_1}^0 - \frac{K_{A_1}^B}{K_{E_2}^B} \omega_{E_2}^0. \quad (3)$$

From Equation (3) we can deduce that the relation between  $\omega_{A_1(LO)}$  and  $\omega_{E_2}$  is linear with a slope of  $K_{A_1}^B/K_{E_2}^B$  and an intercept depending on the n-concentration  $\Delta C$ . Fig. 2 shows the variation of the  $A_1(LO)$  and the  $E_2^H$  peak positions for a 30 mm long 1D line. The  $E_2^H$  peak position remains almost constant but the  $A_1(LO)$  peak varies significantly in some areas. This means that the biaxial stress remains almost constant but the n-carrier concentration increases or decrease in some areas. The mean value of  $A_1(LO)$  and  $E_2^H$  peaks positions for each 1D line is presented in Fig. 3. For all of the studied samples, the relationship between the  $A_1(LO)$  and  $E_2^H$  peak positions is linear as expected from Equation (3) and we obtain a ratio of  $K_{A_1}^B/K_{E_2}^B \approx 1$ . For several lines of one sample (green triangle), a linear regression (in green) with a higher intercept has been done. An increase of the intercept value is an indication of an increase in the n-carrier concentration. These areas correspond to lines presenting a local variation of the  $A_1(LO)$  peak, as observed in Fig. 2. The other data close to the black linear regression do not exhibit high local variation of  $A_1(LO)$  peaks positions. In the future, we then propose to use this calibration to identify areas where the n-doping concentration changes.

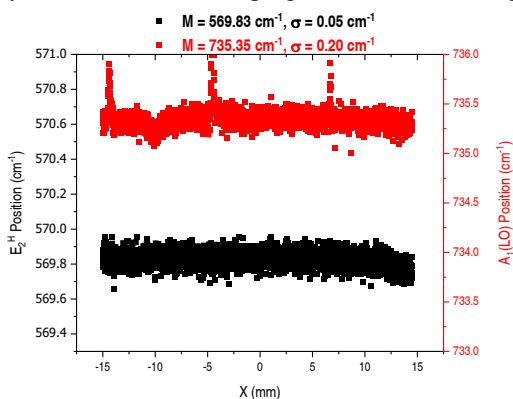


Fig. 2. Variation of  $A_1(LO)$  and  $E_2^H$  peak positions as a function of the distance for a 30 mm long 1D line.

Fig. 4a represents the optical image of a  $174 \mu\text{m}$  diameter etched area (future semi-vertical diode) and Fig 4b is the 2D map of the  $E_2^H$  peaks position for the same area. A relaxation effect is clearly visible after etching, where a gradual change of the stress is observed as we get closer to the edge. Indeed, it is well known that patterned layers relax stress at the free edges [5]. Therefore, for patterned structures, the  $E_2^H$  peak map helps in visualizing biaxial stress distribution. In the future, these

micro-Raman characterizations will be coupled to electrical characterizations of the semi-vertical Schottky diodes to identify the main defects impacting BV and direct current.

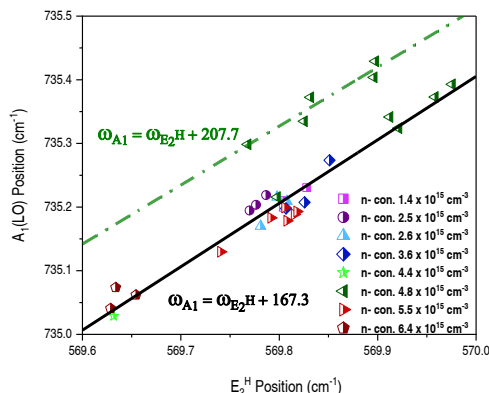


Fig. 3. Evolution of the mean position value of the  $A_1(LO)$  peak as function of the  $E_2$  peak mean positions for the 8 studied samples. Two linear regressions have been performed.

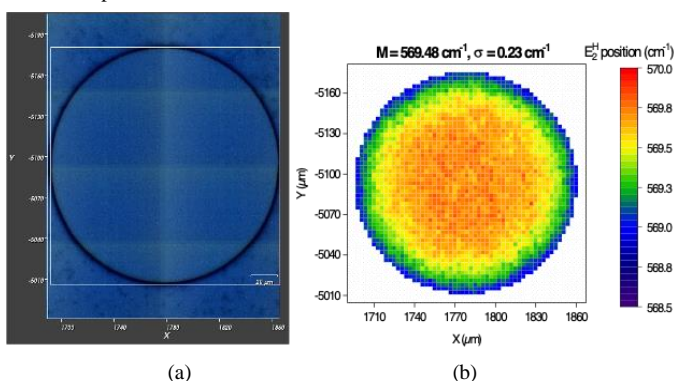


Fig. 4. Optical image of etched n-GaN layer of  $174 \mu\text{m}$  diameter (a) and its corresponding  $E_2^H$  peak positions 2D map.

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