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Correlation of Surface Potential, Free Carrier Concentration and Light Emission in ELO GaN Growth Domains

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We have carried out spatially resolved micro-Raman spectroscopy, cathodoluminescence microscopy and scanning capacitance microscopy in order to obtain a comprehensive understanding about the properties of different domains formed in epitaxial laterally-overgrown GaN. For this purpose a spherical pit was fabricated into the sample by mechanical grinding and polishing, penetrating through to the buffer layer at its center. We found areas showing sharp excitonic luminescence corresponding to local free-carrier concentrations n below $10^{17}\,\text{cm}^{-3}$ as well as domains exhibiting broad luminescence originating from recombination of a doping plasma with n reaching $10^{19}\,\text{cm}^{-3}$. Simultaneously, we observed in the scanning microscopy investigations a substructure which could be explained by the existence of internal space charge regions.

Introduction The technique of epitaxial lateral overgrowth (ELO) has been proven successful in reducing the dislocation density in GaN by a few orders of magnitude [1, 2]. Despite of this technical progress there are still open questions to be answered leading to a better understanding of the structural properties of ELO GaN. While cathodoluminescence microscopy (CL) and micro-Raman spectroscopy are known to be powerful tools for studying structural and optical attributes of materials, the method of scanning capacitance microscopy (SCM) could add to information on the surface topography and capacitance data. Therefore, one could obtain a direct correlation between surface and electrical properties such as effective carrier concentration gradients as described in Ref. [3]. In this paper we present results of a microscopic investigation by these three methods showing an electronic substructure of the domain formed in the overgrown region of the ELO GaN.

Experimental The sample under study was grown on sapphire substrate on top of a 2 μm MOVPE buffer with a facing SiO_2 layer. The latter was patterned by photolithography and wet chemical etching into a periodic mask of hexagons that were on the average 7 μm wide and set 11 μm apart. Subsequent overgrowth of these templates by

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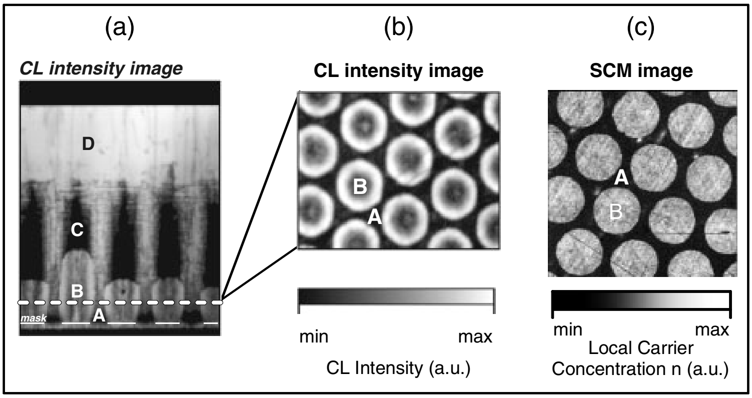

Fig. 1. a) Panchromatic cross-sectional image of CL intensity showing the different ELOG growth domains (A–D). The depth of the plan view images (b) and (c) is indicated by the dashed lines. b) Integral CL intensity and c) inverted SCM image

hydride vapor phase epitaxy (HVPE) results in a 65 μm thick GaN layer which exhibits different growth domains [4] that are visible in the CL intensity image (Fig. 1a).

Areas of initial growth between masks (A) and the facetted lateral overgrowth towards mask centers (B) that is topped by a second growth stage above the masks (C) evolve into a final homogeneous region of high crystal quality near the sample surface (D). To obtain further information about the various domains, in addition to earlier cross-sectional measurements [4], a 2.4 mm wide spherical pit was ground in the ELO GaN, penetrating from the sample surface through to the MOVPE buffer layer at its center. Hence, plan views of *c*-planes as a function of height above the mask are open to microscopy investigations as one moves away from the center of the pit. We shall show in the following interesting details of the columnar growth in ELO-GaN.

Results and Discussion In Fig. 1 we contrast the CL mappings of the cross-sectional and the *c*-plane views. The former in Fig. 1a includes a dash line that indicates the height at which a particular *c*-plane plan view CL mapping has been measured. This latter is displayed in Fig. 1b. The panchromatic CL intensity image (Fig. 1b) clearly exhibits the domains A between the masks (low intensity) and those above the masks (B), showing a substructure with high intensity at the borders and a lowering towards the centers. SCM (Fig. 1c) revealed a constant high local carrier concentration determined as *n*-type across the entire B-regions and a significantly lower one in A. Raman and CL linescans were performed crossing the domain B. The geometry of these linescans is schematically depicted in Fig. 2.

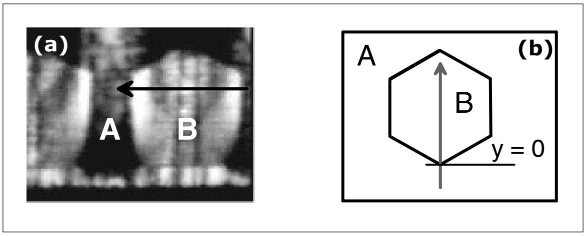

Fig. 2. a) Schematic cross sectional and b) plan view of the scanning mode across the domains A and B as indicated by arrows

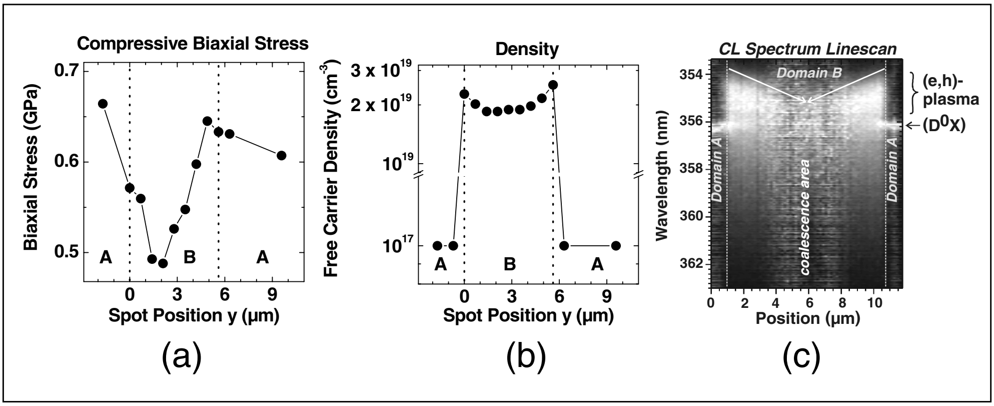

Fig. 3. Results of a Raman linescan at the domain center B across one single column exhibiting the distribution of biaxial stress (a) and free carrier density (b). Analogous linescan of CL spectrum. The donor bound exciton (D^0X) and the plasma luminescence is indicated (c)

In the spectra of the Raman linescans coupled modes of the longitudinal optical A_1-phonon and the plasmon (LPP modes) were detected when the domain B is reached. Hence, one could determine the free carrier concentration as described in Ref. [5]. In addition we used the observed frequency shift of the E_2(high) mode to derive the local strain distribution [6]. In Fig. 3a local correlation of a variation of the free carrier density n (Fig. 3b) and a red-shift of the CL peak maximum (Fig. 3c) from the border to the center of domain B is evident. It should be pointed out, that this red-shift (≈ 1 nm) is not caused by tensile strain. Although there is a variation from border to center (Fig. 3a) the strain still remains compressive.

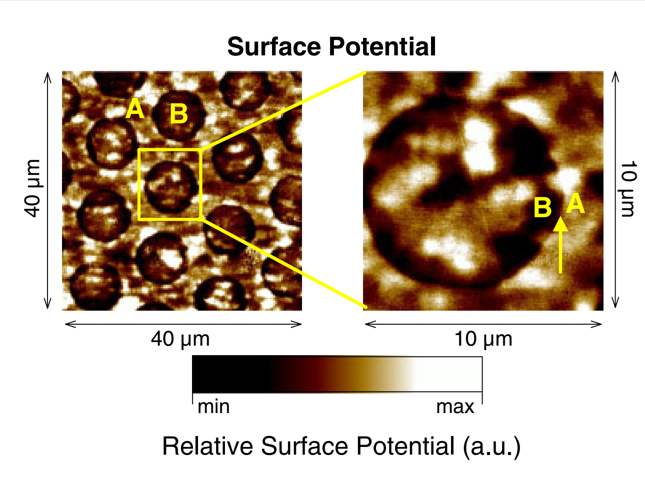

Fig. 4 (online colour). Plan view images of the surface potential at the domain center B. The lightness contrast is due to regions with different carrier concentrations. The transition between both regions A and B is marked by an arrow. The potential difference between minimum and maximum is 0.1 V

Therefore, we arrive at two points that remain unclear. (1) The reason for the red-shift of the CL peak maximum, (2) why the LPP modes are observable only in the region of domain B, not in area A. The sudden disappearance of the latter in domain A together with a strong increase in intensity of the A_1 LO phonon leads to an estimated free carrier concentration below $10^{17}\,\mathrm{cm}^{-3}$, thus to an abrupt change of the free carrier density at the domain borders. To further illustrate a possible explanation we used the method of scanning surface potential microscopy [7] as shown in Fig. 4.

In principle, the surface potential signal reflects the contrast potential difference between the silicon AFM tip and the layer which is controlled by the local semiconductor work function, i.e. it is also sensitive to spatial variations of the Fermi level position due to carrier concentration gradients. The abrupt potential change at the boundaries of domain B is clearly visible in Fig. 4 and can be understood in this context. Different electrical potentials and Fermi level positions should induce internal space charge regions and, finally, the Franz-Keldysh effect in the sample. The latter is then most likely responsible for the red-shift of the CL peak maximum. Furthermore it acts as a barrier for the free carriers, keeping them inside the domains B.

Conclusion The domain structure of ELO GaN as determined by earlier cross-sectional CL and micro-Raman investigations was measured in plan view and spatially resolved. In CL-mappings we observed a substructure of the overgrown regions above the SiO_2-masks while analogous SCM images showed constant carrier concentrations. As determined by Raman linescans a slight variation in compressive strain and free carrier distribution across the areas above the masks is observed. Simultaneously the CL peak maximum exhibits a red-shift from the boundaries towards the centers. The surface potential images also distinguished regions of different free carrier concentrations, but additionally indicate the existence of internal space charge regions. This gives rise to electric fields and the Franz-Keldysh effect. The surface potential thus acts as a barrier for the free carriers which are kept inside these domains.

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