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Lateral and vertical growth of Mg-doped GaN on trench-patterned GaN films

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ABSTRACT

Growth of Mg-doped GaN on trench-patterned GaN films consists of competing lateral and vertical growth fronts that result in regions with different electronic properties. Under typical growth conditions, lateral growth from the trench sidewall occurs at a faster rate than vertical growth from the trench base. When the trench width is sufficiently narrow, the growth fronts from opposite sidewalls coalesce and lead to eventual planarization of the top surface. Secondary electron imaging and cathodoluminescence mapping are used to correlate the morphology and the optical properties of regions resulting from lateral and vertical growth. For our growth conditions, the lateral-to-vertical growth rate ratio is found to be about 2.

The control of electricity in power applications, such as in laptop chargers, power grids, and electric vehicles, places a high demand on semiconductor devices. There is interest in GaN-based thin films because of their superior fundamental properties compared to SiC and Si, such as high values in bandgap energy, electron mobility, and critical breakdown electric fields.[1] The availability of GaN substrates allows the fabrication of vertical *p-n* junctions with low-doped high-mobility drift layers and lateral *p-n* junctions for electric current control. Various techniques for selected area doping for lateral *p-n* junctions are being considered, such as ion implantation, dopant diffusion, and etch-and-regrowth.[2] The latter consists of an *n*-GaN film that is selectively etched to produce vertical trenches, which are then filled with Mg-doped GaN. The regrowth of Mg-doped GaN on trenches involves vertical growth from the lower basal plane of the trench, as well as lateral growth from the trench sidewalls. A sufficiently high concentration and uniform distribution of acceptors in *p*-GaN inside the trenches are required in order to deplete the *n*-GaN channel in vertical-junction FETs to achieve a normally OFF operation.[3] A study of the Mg-doping efficiency at the lateral and vertical growth fronts is essential for optimizing the electronic performance of such devices.

Epitaxial lateral overgrowth (ELO) of GaN is characterized by a high degree of anisotropy that depends on growth parameters. Studies show that at higher reactor pressure or lower growth temperature, the $\{1\bar{1}01\}$ facet (R-plane) can be more stable than the (0001) facet (C-plane).[4] In addition, the intentional introduction of impurities modifies the ratio of lateral vs vertical growth rates of GaN on patterned basal-plane substrates.[5–8] However, there is not much knowledge about the electronic and optical properties of Mg-doped GaN grown parallel (lateral) or perpendicular (vertical) to the basal plane.

We recently reported nonuniform optical properties in Mg-doped GaN epilayers grown on shallow mesa steps.[12] In this work, we further our studies into Mg-doped GaN grown on periodically arranged deep trenches. We use secondary-electron (SE) imaging and cathodoluminescence (CL) monochromatic spectroscopy to map the morphology and the optical properties of Mg-doped GaN. Our findings show regions with different optical characteristics that are independent of trench separation, which correlate well with the formation of R and C facets and variations in acceptor distribution.

The epitaxial structures were grown by metal-organic chemical vapor deposition (MOCVD) on free-standing *c*-plane GaN substrates, with hydrogen as the carrier gas, at a growth temperature of 1050 °C and a reactor pressure of 200 Torr. The Ga and N sources were trimethylgallium (TMGa) and ammonia (NH_3). The precursor for Mg doping is bis(cyclopentadienyl)magnesium (Cp_2Mg). The initial thin film structures consist of 4-μm-thick undoped GaN (*u*-GaN) films grown on (0001) GaN substrates. The masks used for deep etch was SiO_2. We removed the SiO_2 by 10:1 buffered oxide etchant (BOE). The sample was immersed in BOE for 30 min and rinsed with de-ionized water. Chlorine-based inductively coupled plasma (ICP) was used to produce periodic arrays of trenches on the *u*-GaN surface, each trench with a depth of 2 μm and a periodic separation of 4.5, 9, and 25 μm, as shown in Fig. 1(a). The ICP dry etching was performed with an ICP/RF power of 400/70 W at a $Cl_2/BCl_3/Ar$ flow rate of 30/8/5 sccm and at a pressure of 0.67 Pa. The sample was cleaned in acetone, isopropanol alcohol, and de-ionized water before regrowth. No additional surface treatment was conducted. Afterward, Mg-doped GaN was grown on the trench pattern. Mg-doped GaN was grown with a TMGa flow rate of 12 sccm and a Cp_2Mg flow rate of 100 sccm, at a temperature of 975 °C, to obtain a nominal Mg concentration of 3×10^{19} cm^{-3}. The Mg-doped GaN grows preferentially in the trenches, with a tendency to planarize the surface. Post-growth thermal activation of Mg-doped GaN was performed using rapid thermal annealing at 700 °C for 20 min under a nitrogen atmosphere.

The Mg-doped GaN thin films were studied with secondary electron microscopy (SEM) of cross-sectional samples prepared by mechanical polishing using diamond lapping films. The optical properties were studied using a CL system consisting of a JEOL 6300 SEM connected to an Oxford CL2 monochromator and a photomultiplier tube. The microscopic optical characteristics were studied using CL monochromatic mapping by setting the monochromator to specific wavelengths and recording the spatial variation of the luminescence intensity. The electron beam current used for the CL measurements was 100 pA at an accelerating voltage of 7 kV.

Spot mode CL spectra of Mg-doped GaN, taken near the trench base and near the sidewalls in Fig. 1(b), show three characteristic emission peaks observed at 3.4 eV, 3.25 eV, and 2.85 eV.[9–12] The spectrum from near the trench base is dominated by the 2.85 eV peak, while the spectrum from near the sidewalls is dominated by 3.4 eV and 3.25 eV peaks. The 3.4 eV peak is due to near-band edge excitonic transitions at room temperature; the 3.25 eV peak is due to transitions from shallow-donors to Mg-acceptors; and the 2.85 eV peak is due to deep-donor to Mg-acceptor transitions.[10–12] When the Mg concentration increases, the intensities of the 3.4 and 3.25 eV peaks decrease and the 2.85 eV peak increases.[9–12]

Figure 2 shows SE and CL images of Mg-doped GaN grown on a trench pattern with a period of 9 μm and a top mesa width of 0.5 μm. Mg-doped GaN has a brighter contrast than *u*-GaN in the SE image.[13] The trench sidewall is 2 μm in height and it is tilted approximately $\pm$ 12° from vertical. The growth of Mg-doped GaN in the trenches consists of lateral growth from the sidewall and vertical growth from the trench base. Notches at the top surface are observed at the center of trenches. The monochromatic CL images of Mg-doped GaN show complementary emissions between near-band edge (3.4 eV) and *p*-type-related (2.85 eV) emissions: the 3.4 and 3.25 eV emissions show a higher intensity in the vicinity of sidewalls and a lower intensity at the trench base, while the opposite being true for the 2.85 eV emission, which exhibits a lower intensity in the vicinity of sidewalls and a higher intensity at the trench base.

Figure 3 is for trenches with a narrower width of 4.5 μm. The SE image shows a flat Mg-doped GaN surface, suggesting that the growth fronts from opposite sides of the trench have fully coalesced, producing a *c*-plane growth front. The monochromatic CL images show complementary emissions in a similar manner to those in Fig. 2. In the 2.85 eV CL image, the bright region at the trench base is observed to

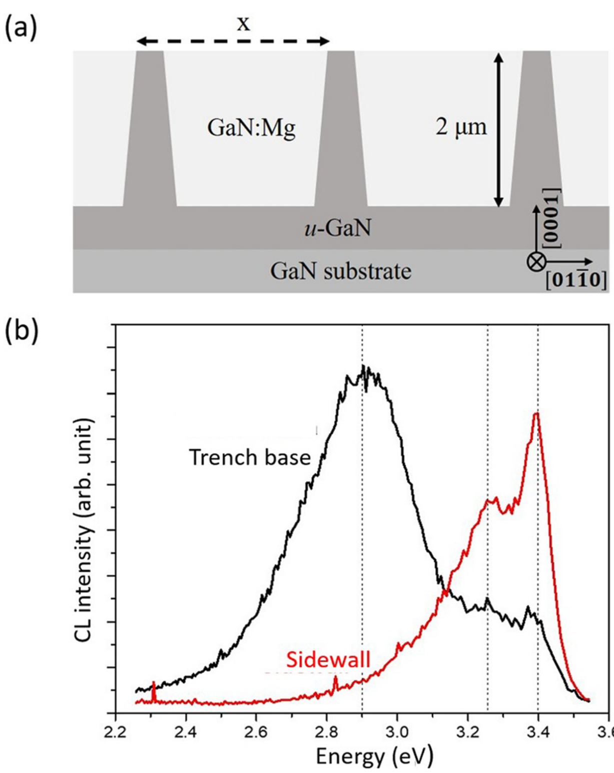

FIG. 1. Mg-doped GaN on GaN trench patterns. (a) Schematic diagram of the trench pattern geometry. The trench periods are x = 4.5, 9, and 25 μm, and the trench depth is 2 μm. The top mesa width is 0.5 μm. Mg-doped GaN was subsequently deposited with the intention to fill in the trench pattern. (b) Spot-mode cathodoluminescence spectra indicate *p*-type behavior near the trench base and semi-insulating behavior near the sidewalls.[12]

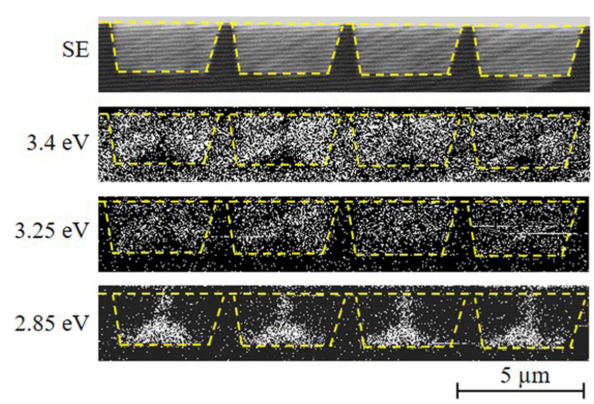

FIG. 2. Cross-sectional secondary-electron and monochromatic CL images of Mg-doped GaN grown on trench patterns with a 9 μm period and a 0.5 μm top mesa width. Mg-doped GaN has a brighter contrast than *u*-GaN in this image. Its surface is flat next to the top of the mesa and decreases after a distance of ~3 μm, leading to a notch at the top center of the trench. The *u*-GaN has a strong emission at 3.4 eV. The Mg-doped GaN show a strong emission at 2.85 eV at the trench base, indicative of its *p*-type nature. Strong emissions at 3.4 eV and 3.25 eV are observed near the sidewall, indicative of a semi-insulating nature.[12]

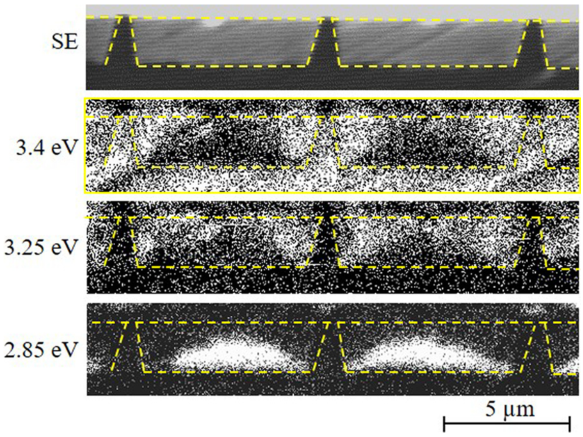

FIG. 3. Cross-sectional secondary-electron and monochromatic CL images of Mg-doped GaN grown on trench patterns with a 4.5 μm period and a 0.5 μm top mesa width. The Mg-doped GaN from opposite sides coalesce, and a flat surface is achieved. A strong emission at 2.85 eV is observed at the trench base, a characteristic of *p*-type GaN. Strong emissions at 3.4 eV and 3.25 eV are observed near the sidewall, indicative of a semi-insulating nature.[12]

stretch toward the surface. This suggests that a c-plane growth front formed after the coalescence of the lateral fronts at the trench center.

Figure 4 shows cross-sectional SE and CL images for the case of a trench width of 25 μm. The specimen in Fig. 4 is tilted, with the top surface offering a wider tilted section and showing a thin *p*-GaN on the flattop of the mesa. Anisotropic growth and complementary emissions are observed near sidewalls and trench bases, as discussed earlier. A strong emission at 2.85 eV is also observed on the flat top of the mesa, which is weakly observed in the edge-on cross-sectional images in Figs. 2 and 3.

The anisotropic growth of Mg-doped GaN films results from the presence of the sidewalls.[14,15] The sidewall can be viewed as a highly tilted facet consisting of a high density of basal-plane steps, with each step acting as an effective site for capture of adatoms, leading to lateral growth.[14,15] The lateral growth rate has been reported to be affected by the growth temperature and chamber pressure.[4] In addition, Mg makes adsorption of Ga favorable on the $\{1\bar{1}01\}$ facets and, thus, promotes the accumulation of adatoms in the vicinity of sidewalls.[5] The competition between lateral and vertical growth results in the reduction of the layer thickness with distance from the mesa, as observed in the SE image in Fig. 4(a). Adatoms on the top of the mesa will diffuse preferentially to the edges where they will attach to the c-plane steps, contributing to lateral growth and the formation of R planes. If the top width of the mesa is larger than the adatom diffusion length, growth on the top portion of the mesa will proceed. This can be observed in Ref. 12.

The variation in luminescence characteristics in Mg-doped GaN has been attributed to lateral growth of GaN on highly tilted facets with reduced Mg doping efficiency, leading to the formation of semi-insulating regions (p^--GaN).[12,16]

The charactestics of the *p*-GaN and p^--GaN regions can be visualized in the monochromatic CL images in Figs. 2–4. The growth fronts are shown in the schematic diagrams in Fig. 5. The *p*-GaN and

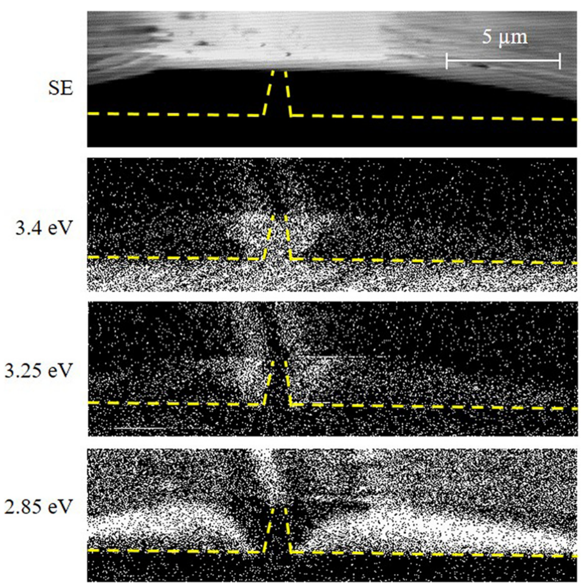

FIG. 4. Tilted cross-sectional images of Mg-doped GaN grown on a trench pattern with a 25 μm period. The secondary-electron (SE) image shows the surface morphology. A strong 3.4 eV emission is observed in the u-GaN and in the trench regions next to the sidewalls. (c) A strong 2.85 eV emission is observed on top of the fin structure in addition to the region at the bottom of the trench. The 3.25 eV emission is complementary to the 2.85 eV emission.

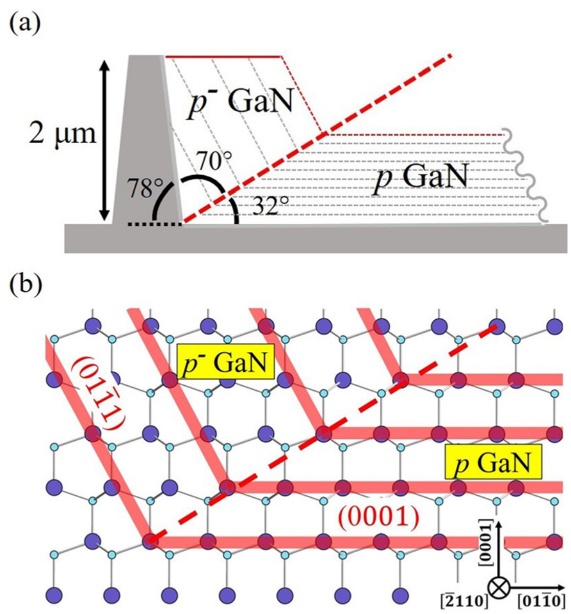

FIG. 5. Schematic diagrams of Mg-doped GaN grown on trench patterns. (a) The sidewall inclination of 12° from the vertical is a result of ICP etching. The *p*-GaN and p^--GaN regions are separated by a boundary (red dashed line) making an angle of 32° with the basal plane, independent of trench widths. (b) The boundary between *p*-GaN and p^--GaN regions corresponds the coalescence of growth fronts on $\{01\bar{1}1\}$ and {0001} planes, with a ratio of lateral to vertical growth of about 2.

p^{-}-GaN regions are separated by a boundary (the red dashed line) tilted counterclockwise by about 32° from the basal plane, as depicted in Fig. 5(a). This angle is characteristic of growth involving lateral and vertical growth, and in our case, it is independent of the trench widths. A correlation with the crystal lattice shows that the boundary is the intersection of the $\{1\bar{1}01\}$ growth front originating from the sidewall and the vertical (0001) growth front. Figure 5(b) shows that when a (0001) monolayer advances, two monolayers on a $\{1\bar{1}01\}$ plane should form to provide coincidence between the lateral and vertical growth fronts. It has been observed in various cases that the lateral growth from the sidewall is faster than the vertical growth. In the case of a narrow trench width of 5 μm, lateral growth from the two opposite sidewalls coalesces to fill the trench. This leads to the reappearance of vertical growth near the center top portion of the Mg-doped GaN film, leading to planarization of the film surface, as evidenced by the CL emission at 2.85 eV in Fig. 3.

In summary, we have studied the growth of Mg-doped GaN on trench patterns. We have observed two growth fronts with different electronic characteristics: a $\{1\bar{1}01\}$ lateral growth front from the sidewalls and a (0001) vertical growth front from the bottom of the trenches that meet at a boundary making an angle of about 30 degrees with the basal plane. The boundary angle is determined by the coincidence of lattice points belonging to both facets. The lateral growth rate is about 2 times the vertical growth rate. The CL characteristics indicate that the lateral growth region is semi-insulating, while the vertical growth region is p-type. These observations are consistent with other observations of growth under different geometries and growth conditions,[12,16] where the optical properties are attributed to Mg incorporation on different facets, and are related to different doping efficiencies. These results are important in the development of vertical devices for GaN power electronics where etch-and-regrowth of Mg-doped GaN is involved, in particular, for trenches for guard rings and p–n junction Schottky diodes used for edge termination.[2]

AUTHORS' CONTRIBUTIONS

P.Y.S. and H.L. contributed equally to this work.

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DATA AVAILABILITY

The data that support the findings of this study are available within the article.

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