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Growth of high quality ZnO thin films with a homonucleation on sapphire

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ZnO thin films were epitaxially grown on c-plane sapphire substrates by plasma-assisted molecular beam epitaxy. A low temperature homonucleation ZnO layer was found crucial at the interfacial region to absorb the defects formed by the lattice mismatch between the sapphire and ZnO, resulting in a smooth surface that enables smooth 2D epitaxial growth. High quality ZnO films were achieved after careful optimization of critical growth conditions: the sequence of Zn and O source shutters, growth temperature for both the ZnO nucleation and growth layer, and Zn/O ratio. Oxygen plasma pretreatment was not applied prior to the growth, thus shortening the growth time and reducing oxidation of the metallic sources. Resultant epitaxial ZnO films on sapphire demonstrated a root-mean-square surface roughness of 0.373 nm for $1\ \mu\text{m} \times 1\ \mu\text{m}$ atomic force microscope images with clear hexagonal structure and terrace steps. The x-ray diffraction full width at half maximum (FWHM) for ω and $\omega-2\theta$ ZnO (0002) triple-crystal rocking curves were measured to be 13 and 26 arc/s, respectively. This FWHM value is lower than any reported to date in the literature, with ω and $\omega-2\theta$ values indicating excellent coherence of the epitaxial layer along the interface and the growth direction, accordingly. These x-ray diffraction and surface roughness values are lower than those obtained using common nucleation layers such as MgO, indicating that growth with ZnO nucleation layers on sapphire may lead to higher quality electrical and optical devices. © 2013 American Vacuum Society. [<http://dx.doi.org/10.1116/1.4813918>]

I. INTRODUCTION

Zinc oxide (ZnO) is an attractive material for high efficiency ultraviolet (UV) optoelectronics devices, such as solar-blind photodetectors,^{1,2} laser diodes (LDs),³ and light emitting diodes (LEDs).^{4,5} Different methods have been used to grow ZnO-based thin films, such as pulsed laser deposition (PLD),⁶ metal-organic chemical vapor deposition (MOCVD),⁷ molecular beam epitaxy (MBE),^{8,9} radio-frequency (RF) magnetron sputtering,¹⁰ and sol-gel.¹¹ Among them, MBE has been applied to obtain single crystal ZnO films which show potential for UV light emitters. Optically and electrically pumped lasing at room-temperature (RT) from ZnO has been reported.^{12,13}

Much of the effort focused on ZnO growth on sapphire is due to its relative low cost^{14–18} and the many potential benefits of ZnO to optoelectronic devices. However, there is a large in-plane lattice mismatch (18%) between c-oriented ZnO and the sapphire, typically resulting in a high dislocation density of more than $10^9\ \text{cm}^{-2}$ in epitaxial layers. Chen *et al.*¹⁴ reported the smallest full width at half maximum (FWHM) to date of the x-ray diffraction (XRD) (0002) rocking curve (RC) (~ 18 arc sec), however the surface roughness

of the films were not reported. They found a 30° rotation in the crystal orientation of the ZnO epilayer on the sapphire substrate. To improve the crystal quality, MgO was used as a hetero-buffer between sapphire and the ZnO epi-layer to accommodate the lattice mismatch and eliminate the 30° rotation,^{9,14} thus improving the electrical and structural properties of the ZnO epilayers. Chu *et al.*¹⁸ demonstrated an epi-ZnO film with root-mean-square (RMS) roughness of 0.65 nm, but with a broad FWHM XRD rocking curve (~ 200 arc sec). H_2O_2 was used as oxygen precursor in MBE,¹⁹ resulting in a ZnO film with surface roughness of 0.2 nm and XRD FWHM of 30 arc sec. In this study, by developing a low temperature (LT) homonucleation ZnO layer and carefully optimizing the growth conditions, we were able to obtain high quality ZnO thin films with high crystalline quality and subnanometer surface roughness, representing a significant improvement over other reported nucleation layers for ZnO on sapphire.

II. EXPERIMENT

ZnO was grown on (0001) $\alpha\text{-Al}_2\text{O}_3$ (c-plane sapphire substrates) by plasma-assisted molecular beam epitaxy (PAMBE).⁸ Base pressure in the growth chamber was $\sim 2 \times 10^{-10}$ Torr. Elemental Zn (6N) was evaporated from standard hot-lipped Knudsen cell and O (6N) fluxes were

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supplied by a RF radical cell ($f_0 = 13.56$ MHz). During the growth of ZnO layers, the pressure in the chamber was maintained around 3×10^{-6} to 5×10^{-6} Torr. To increase the homogeneity of heat conduction during the growth, $1 \mu\text{m}$ of titanium was deposited on the backside of the sapphire with a Temescal E-beam evaporation system (model FC-2000). The sample was thereafter degreased with iso-propanol and dried with a nitrogen gun. After this cleaning procedure, the substrate was immediately loaded on an indium free molybdenum holder and thermally cleaned at 600°C in a buffer chamber (10^{-9} Torr) for 4 h before transfer to the growth chamber.

Sapphire substrates pretreated with oxygen plasma have been reported critical for initial 2D ZnO growth in order to form an oxygen terminated surface. Although the pretreatment is largely used for growth of ZnO, the excess oxygen has the deteriorating effect of accelerating the oxidation of metallic sources, i.e., Zn, in the MBE chamber, especially when outgassing at high temperature (HT) under the oxygen environment, causing a measurable shift in the Zn flux over time. This, in turn, results in increased maintenance for the MBE chamber in order to replenish the oxidized Zn source material. Sapphire substrates discussed in this study were not treated with oxygen plasma, greatly improving the up-time of the system by reducing source oxidation and vacuum regenerative maintenance. The oxygen treatment is not necessary in this case because the sapphire substrates are already oxygen-terminated due to long exposure to air making the pretreatment redundant.

High-resolution x-ray diffraction was performed using a PANalytical X'Pert materials research diffractometers (MRD) diffractometer. A multilayer focusing mirror and a four-bounce Hybrid Ge(220) monochromator provide collimated (18° arc/s divergence) and monochromatic incident Cu $K_{\alpha 1}$ radiation, while a three-bounce Ge (220) analyzer allows separation of coherent and diffuse scattering, thus permitting the visualization and measurement of the spatial distribution of scattered radiation. Triple crystal (TC) ω - 2θ and ω x-ray RCs, measured in the vicinity of symmetrical (0002) reflection were used for characterization of the layer strain, composition, and crystal perfection. Triple crystal ω - $2\theta/\omega$ reciprocal space maps (RSM) measured in the vicinity of the (0002) and (114) reflections were used to visualize angle distribution of coherent and diffuse scattered x-ray radiation and specify spatial distribution of crystalline defects. The vertical and lateral coherence lengths of the substrate and epitaxial layers, derived from the FWHM of corresponding peaks of the ω - 2θ and ω RCs, were used for evaluating the crystal perfection of the epitaxial structures. The density of threading dislocation loops in the volume of the epitaxial structure and lateral coherence length of the epitaxial layer were calculated from the FWHM of ω rocking curve, measured at the maximum of the epilayer diffraction peak.

III. RESULTS AND DISCUSSION

A. Typical growth

The typical growth conditions are listed in Table I. The deposition of ZnO was monitored *in situ* by reflection

TABLE I. Typical growth conditions for ZnO.

	Nucleation layer	ZnO epi-layer
Growth temperature	350°C	500°C
Zinc temperature	360°C	350°C
Oxygen flow rate/power	1.5 sccm/350 W	1.1 sccm/350 W
Growth rate	$0.21 \mu\text{m/h}$	$\sim 0.15 \mu\text{m/h}$

high-energy electron diffraction (RHEED). Similar to GaN growth on sapphire, high quality films can be obtained by using a low temperature buffer. Here a LT ZnO homonucleation layer was first grown at 350°C on the sapphire substrate to act as nucleation and buffer layer. A growth rate around $0.21 \mu\text{m/h}$ was achieved for the nucleation layer as monitored by laser reflectometry. Because the sapphire substrate is oxygen terminated, Zn is preferred to arrive at the surface and combine with the surface oxygen with better migration ability. The Zn shutter was opened first for 3 s, allowing for about one monolayer of deposition followed by opening of the oxygen shutter. This sequence reliably generated terrace-step morphology. After 7 min of growth, a 25 nm ZnO nucleation was formed on the substrate. The RHEED pattern of the nucleation layer, shown in Fig. 1(a), was initially spotty, indicating a roughening of the growth surface. The pattern gradually transformed into a sharp streaky pattern [Fig. 1(b)] after annealing at 600°C for 30 min, indicating the nucleation layer was clean and flat after the annealing process. A subsequent HT ZnO layer was grown above the nucleation layer at 500°C . The Zn to oxygen ratio was maintained for oxygen-rich conditions at low flux to assure a slow growth rate for HT ZnO layer, in this case, $0.15 \mu\text{m/h}$. This HT regime allowed for homogeneous diffusion of the adatoms and prevention of 3D growth. The RHEED pattern after a 500 nm HT layer was clearly streaky, indicating 2D growth, as shown in Fig. 1(c).

B. Zn flux

We found the following stoichiometric condition for ZnO films at a growth temperature of 500°C : a Zn cell temperature of 370 to 380°C with oxygen flux of 1.1 sccm and RF power of 350 W. Since most of the literature concludes the best growth happens at the stoichiometric condition, we began to investigate the Zn cell temperature at the stoichiometric point, in our case, with Zn cell temperature of 378°C . The atomic force microscope (AFM) image was not as good as we expected, as shown in Fig. 2(d), with RMS roughness of 6.13 nm, implying that a more oxygen rich condition was needed. We therefore decreased the Zn cell temperature as shown in Fig. 2. The roughness was greatly improved at Zn cell temperatures below 370°C and clear terraces were observed. We chose a Zn cell temperature of 350°C for subsequent studies since it provides good morphology, and higher Zn cell temperatures accelerate the oxidation of the Zn cell.

C. Growth temperature

Most studies in the literature have investigated the influence of growth temperature on the properties of HT growth

FIG. 1. (Color online) RHEED patterns of LT nucleation layer (a) before annealing, (b) after annealing; (c) 500 nm HT ZnO layer.

layers, without consideration of the influence of the temperature on the LT nucleation layer.¹⁹ To optimize the growth conditions, we studied the influence of the growth temperature on both the HT growth layer and the LT nucleation layer. The growth procedure was identical as mentioned earlier, except for varying of the growth temperature. The relationship between RMS roughness and growth temperature is shown in Fig. 3. It was found that the higher LT nucleation growth temperature ($T_{LT} = 350^\circ\text{C}$) provides better morphology for all growth temperatures studied. The majority of prior studies have utilized growth temperatures for HT layer up to 700°C . Here, as shown in Fig. 3, we

observe that the surface morphology deteriorates at temperature above 550°C , suggesting lower growth temperatures are preferred. From Fig. 3, we have identified the best growth conditions to be $T_{LT} = 350^\circ\text{C}$ and $T_{HT} = 500^\circ\text{C}$. Due to the lattice mismatch of ZnO and sapphire, there are always considerable dislocations found in the films. As shown in the inset of Fig. 2, although both films showed good surface RMS roughness and even terrace steps were observed, there were a large density ($4.4 \times 10^9/\text{cm}^2$) of pits in the films grown using a $T_{LT} = 300^\circ\text{C}$, even with the best HT growth conditions. However, the pits were nearly eliminated at

FIG. 2. (Color online) RMS roughness as function of growth temperature for LT nucleation temperature of 300°C and 350°C . The inset graphs are $1 \mu\text{m} \times 1 \mu\text{m}$ AFM images of the best films grown under the two nucleation temperatures.

FIG. 3. (Color online) RMS roughness as function of Zn cell temperature around stoichiometric conditions. The inset graphs are $5 \mu\text{m} \times 5 \mu\text{m}$ AFM images with Zn cell temperature of (a) 350°C , (b) 365°C , (c) 370°C , and (d) 378°C .

$T_{LT} = 350^\circ\text{C}$, demonstrating that the higher T_{LT} reduces the number of defects reaching the surface.

D. X-ray diffraction characterization

The triple-crystal ω - 2θ RC in the vicinity of ZnO (0002) reflection [Fig. 4(a)] is a smooth slightly asymmetrical (on the lower angle side) curve without interference fringes, with FWHM = 26 arc/s, corresponding to 640 nm vertical coherence length of the layer. This length is less in comparison with the total thickness of epitaxial layer ~ 940 nm, based on technological evaluation. ZnO 2θ angle peak position on the ω - 2θ RC indicates that the elastic stress in this layer is almost fully relaxed by creation of edge dislocations.

All noted features clearly demonstrate an existence of closed dislocation loops with edge segments in the volume of epitaxial layer,²⁰ created at the final stage of the defects creation procedure, after appearance of open dislocation

loops and edge dislocations on the interface.^{21,22} These closed dislocation loops appear due to the structural transformation of point defects, continuously creating on the growth front: diffused inward and accumulated in predislocation clusters above the interface, these point defects induce secondary elastic stress at the bottom of the layer, which finally transform accumulated point defects to closed dislocation loops.^{21,22}

The density of created dislocation loops depends on the number of point defects, created on the growth front, i.e., perfection of growth conditions, and the energy of structural transformation of predislocation clusters to dislocation loops, i.e., elastic properties of ZnO. The final length of these loops is determined by the duration of the growth procedure after nucleation of dislocation loops.

The thickness of the bottom sublayer, filled out by closed dislocation loops may be roughly evaluated by the difference between the total thickness and the vertical coherence length of the layer, is derived from the FWHM of the ω - 2θ layer peak. The left-side asymmetry of the ω - 2θ RC is related to additional compressed elastic stress, induced by predislocation clusters and closed dislocation loops.²³

The triple-crystal ω RC measured on the maximum of the ZnO (0002) peak [Fig. 4(b)] is a convolution of the narrow curve (FWHM = 13.3 arc/s) and a wide diffuse base, related to the bottom structurally deteriorated sublayer with a FWHM of ~ 120 arc/s. The FWHM of the (0002) ZnO peak (13 arc/s) is below the highest crystallinity reported to date in the literature (18 arc/s).¹⁴ A LT nucleation layer is crucial on the interfacial region to absorb these defects and produces a smooth surface that enables the following 2D epitaxial growth. The RHEED pattern for nucleation layer indicates the morphology of the initial annealed growth is smooth, allowing the subsequent growth of a high quality epilayer. Direct evaluation of the density of dislocation loops from the FWHM of these peaks [narrow curve and wide diffuse base in Fig. 4(b)] yields values of $\sim 1.7 \times 10^5 \text{ cm}^{-2}$ and $1.6 \times 10^7 \text{ cm}^{-2}$, respectively.^{24,25} Based on our understanding, the second number correlates specifically with the density of closed dislocation loops at the bottom of the layer, while the FWHM of the narrow central coherent peak directly correlates with the lateral coherence length ($\sim 4 \mu\text{m}$ in this case), and not the density of dislocation loops.²⁶ The narrow width of the central ω RC peak correlates with the crystalline perfection of ZnO layer, but not directly, real more complicated situation is described below.^{26,27}

Typical ZnO layer grown on sapphire substrate has open primary and secondary threading dislocation loops (most probably, screw type), created at the initial stages of epitaxial growth.^{21,22} These created dislocation loops penetrate through entire epitaxial layer, following from the bottom interface to the growth front. In highly lattice-mismatched epitaxial structures the total density of these dislocation loops may be roughly evaluated $\sim 10^8 \text{ cm}^{-2}$. True screw dislocation loops have no edge segments in the volume of epitaxial layer and do not affect vertical coherence of epitaxial layers (do not increase FWHM of the ω - 2θ RC). At rather low density, they also do not affect lateral coherence of

FIG. 4. (Color online) (a) Triple-crystal ω - 2θ RC in the vicinity of ZnO (0002) reflection. Visual asymmetry of the RC is related to additional compressed elastic stress, induced by predislocation clusters and closed dislocation loops; (b) triple-crystal ω RC of ZnO (0002) reflection. The inset is the magnified graph in the dashed area.

epitaxial layer and do not increase FWHM of the central coherent peak of the ω RC.²⁸

Edge dislocations appear on the interface immediately after creation of primary and secondary dislocation loops as a part of chain defects creation procedure²² to almost fully accommodate initial elastic strain and fully relax initial elastic stress. Despite the high density of these dislocations ($\sim 10^6 \text{ cm}^{-1}$ or even more), located on the interface, they do not affect vertical and lateral coherences of epitaxial layers and do not increase FWHM of the ω - 2θ and ω RCs. Edge dislocations do not deteriorate ad-atoms migration on the growth front and do not deteriorate 2D epitaxial growth mode.^{23,26,28,29}

The creation of closed dislocation loops in the volume of the layer, just above the interface, is a final stage of defects creation process.²² But appearance of these ramified loops in the volume of the layer may be significantly postponed by perfect growth condition, which slow down accumulation and transformation of point defects at the bottom of the layer.^{22,23,28,29} The created closed dislocation loops rise up, following the growth front with the lag, specified by growth conditions and elastic properties of epitaxial layer. In case of GaN layer, it may reach 900–1000 nm,^{30,31} in case of AlN ~ 200 to 250 nm.^{28,29} The density of closed dislocation loops is $\sim 10^8 \text{ cm}^{-2}$, but usually they are nonhomogeneously distributed in the volume of the epitaxial layer and can create a kind of dislocation clusters with large spaces between them, mostly free of extended crystalline defects.^{28,29} These overlapped defect-free areas may affect both vertical and lateral coherences of epitaxial layers,²⁸ or just vertical coherence of the layers.²⁹ Elongation of x-ray radiation diffuse scattered around ZnO (11–24) diffraction spot along Q_x direction instead of ω direction (Fig. 5) is related to the lateral correlation of closed dislocation loops and anisotropic distribution of induced elastic stress in the volume of ZnO layer.³¹ To directly confirm the suggested types, density and spatial

distribution of crystalline defects, conventional cross-section TEM is desirable.

IV. SUMMARY AND CONCLUSIONS

High quality ZnO thin films were epitaxially grown on c-plane sapphire substrates by PAMBE. The oxygen plasma pretreatment was found unnecessary in this case, indicating an improvement of the efficiency of growth and time of Zn source and MBE chamber maintenances. By simply applying a LT homonucleation ZnO layer, high quality ZnO films were achieved. Opening Zn source shutter first results in higher quality nucleation and benefits the high temperature growth afterward. Growth temperatures and Zn/O ratio for both the ZnO LT nucleation and HT layer were optimized. The best growth temperature was found to be 350 °C for the LT nucleation layer and 500 °C for HT layer. Under slightly oxygen rich conditions, epitaxial growth of ZnO on sapphire was achieved with resultant films having the highest demonstrated quality as compared to known published results. The RMS surface roughness was 0.373 nm for a $1 \mu\text{m} \times 1 \mu\text{m}$ area with clear hexagonal terrace steps shown in AFM images. TC ω - 2θ and ω x-ray RC, measured in the vicinity of symmetrical (0002) reflection were used for characterization of the layer strain, composition, and crystal perfection. The ω rocking curve for the ZnO (0002) had a FWHM of 13 arc/s, lower than any prior value reported in the literature, indicating high quality of the grown material. This research demonstrates a simple method for realizing high quality ZnO thin films of very high quality without substrate surface treatment or introduction of other intermediate layers such as MgO.

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FIG. 5. (Color online) Asymmetrical Reciprocal Space Map around ZnO (11–24) diffraction spot. Drawn line shows the ω scan direction.

- ¹S. Han *et al.*, *Appl. Phys. Lett.* **99**, 242105 (2011).
- ²H. L. Liang *et al.*, *Appl. Phys. Lett.* **98**, 221902 (2011).
- ³H. Long, G. J. Fang, S. Z. Li, X. M. Mo, H. N. Wang, H. H. Huang, Q. K. Jiang, J. B. Wang, and X. Z. Zhao, *IEEE Electron Device Lett.* **32**, 54 (2011).
- ⁴A. Tsukazaki *et al.*, *Nature Mater.* **4**, 42 (2005).
- ⁵K. Nakahara *et al.*, *Appl. Phys. Lett.* **97**, 013501 (2010).
- ⁶E. M. Kaidashev *et al.*, *Appl. Phys. Lett.* **82**, 3901 (2003).
- ⁷W. Z. Xu, Z. Z. Ye, Y. J. Zeng, L. P. Zhu, B. H. Zhao, L. Jiang, J. G. Lu, H. P. He, and S. B. Zhang, *Appl. Phys. Lett.* **88**, 173506 (2006).
- ⁸M. Wei, R. C. Boutwell, G. A. Garrett, K. Goodman, P. Rotell, M. Wraback, and W. V. Schoenfeld, *J. Alloys Compd.* **552**, 127 (2013).
- ⁹A. El-Shaer, A. Bakin, M. Al-Suleiman, S. Ivanov, A. C. Mofor, and A. Waag, *Superlattices Microstruct.* **42**, 129 (2007).
- ¹⁰K. Sivakumar and S. M. Rossnagel, *J. Vac. Sci. Technol. A* **28**, 515 (2010).
- ¹¹M. Wei, R. C. Boutwell, J. W. Mares, A. Scheurer, and W. V. Schoenfeld, *Appl. Phys. Lett.* **98**, 261913 (2011).
- ¹²D. M. Bagnall, Y. F. Chen, Z. Zhu, T. Yao, S. Koyama, M. Y. Shen, and T. Goto, *Appl. Phys. Lett.* **70**, 2230 (1997).
- ¹³H. Zhu *et al.*, *Adv. Mater.* **22**, 1877 (2010).
- ¹⁴Y. F. Chen, D. M. Bagnall, H. J. Koh, K. T. Park, K. Hiraga, Z. Q. Zhu, and T. Yao, *J. Appl. Phys.* **84**, 3912 (1998).

- ¹⁵T. E. Murphy, D. Y. Chen, E. Cagin, and J. D. Phillips, *J. Vac. Sci. Technol. B* **23**, 1277 (2005).
- ¹⁶J. S. Wang, C. S. Yang, M. J. Liou, C. X. Wu, K. C. Chiu, and W. C. Chou, *J. Cryst. Growth* **310**, 4503 (2008).
- ¹⁷B. Y. Zhang, B. Yao, S. P. Wang, Y. F. Li, C. X. Shan, J. Y. Zhang, B. H. Li, Z. Z. Zhang, and D. Z. Shen, *J. Alloys Compd.* **503**, 155 (2010).
- ¹⁸S. Chu, M. Morshed, L. Li, J. Huang, and J. L. Liu, *J. Cryst. Growth* **325**, 36 (2011).
- ¹⁹A. El-Shaer, A. C. Mofor, A. Bakin, M. Kreye, and A. Waag, *Superlattices Microstruct.* **38**, 265 (2005).
- ²⁰Z. Liliental-Weber and D. Cherns, *J. Appl. Phys.* **89**, 7833 (2001).
- ²¹N. Faleev, N. Sustersic, N. Bhargava, J. Kolodzey, A. Yu. Kazimirov, and C. Honsberg, *J. Cryst. Growth* **365**, 44 (2013).
- ²²N. Faleev, N. Sustersic, N. Bhargava, J. Kolodzey, S. Magonov, D. J. Smith, and C. Honsberg, *J. Cryst. Growth* **365**, 35 (2013).
- ²³N. Faleev, H. Temkin, I. Ahmad, M. Holtz, and Yu. Melnik, *J. Appl. Phys.* **98**, 123508 (2005).
- ²⁴J. E. Ayers, L. J. Schowalter, and S. K. Ghandhi, *J. Cryst. Growth* **125**, 329 (1992).
- ²⁵J. E. Ayers, *J. Cryst. Growth* **135**, 71 (1994).
- ²⁶V. M. Kaganer, O. Brandt, A. Trampert, and K. H. Ploog, *Phys. Rev. B* **72**, 045423 (2005).
- ²⁷V. M. Kaganer, R. Kohler, M. Schmidbauer, R. Opitz, and B. Jenichen, *Phys. Rev. B* **55**, 1793 (1997).
- ²⁸N. Faleev, H. Lu, and W. J. Schaff, *J. Appl. Phys.* **101**, 093516 (2007).
- ²⁹N. Faleev and I. Levin, *J. Appl. Phys.* **107**, 113529 (2010).
- ³⁰H. Heinke, V. Kirchner, H. Selke, R. Chierchia, R. Ebel, S. Einfeldt, and H. Hommel, *J. Phys. D: Appl. Phys.* **34**, A25 (2001).
- ³¹T. Metzger *et al.*, *Phys. Status Solidi. A* **162**, 529 (1997).