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主 論 文 の 要 旨

論文題目 Growth and characterization of nonpolar a-plane GaN and ohmic contacts of nonpolar p-type a-plane GaN（無極性面 a 面 GaN の結晶成長と評価及び無極性 a 面 p 型 GaN のオーミックコンタクト）

氏　　名 孫　志壽

論 文 内 容 の 要 旨

Nonpolar a-plane GaN layers were grown on r-plane sapphire substrates with -0.2°-off-axis tilted in the c-axis [0001] direction by MOPVE system. Various methods were investigated to improve crystalline quality and nonpolar a-plane InGaN/GaN-based LED performance. The epitaxial experiments consist of seven chapters. First, mutil buffer layer (MBL) technique has been investigated. For the two step (3D-2D) growth process, high-temperature (HT) nucleation layer was adopted instead of low-temperature nucleation layer. HT nucleation layer was effective to form large nuclei, which lead to 3D-2D growth process more easily easily and effectively obtain the fully coalesced a-plane GaN layer. The MBL technique was modified from 3D-2D growth process. In comparison with one-step (2D) growth mode, The XRC FWHM value along c- and m-axis directions was reduced in two-step growth mode. Especially, The XRC FWHM value of one-step sample was almost double values along the m-axis direction in comparison with the two-step sample.

Next, to improve crystalline quality of a-plane GaN layer, the multi SiNx interlayers, which is in-situ method, were investigated by SiNx nano mask. The extremely thin multi SiNx interlayers were partially deposited by various loop system on the 2nd buffer layer and the 3rd buffer layer. After insertion of optimal multi SiNx interlayers loop, the XRC FWHM anisotropy of the a-plane GaN layer was significantly reduced along c-axis. The surface morphologies were obtained smooth surface. However, the BSFs density and XRC FWHM anisotropy of the a-plane GaN layer along m-axis were still not enough to fabricate the high efficiency a-plane GaN LED device.

To overcome the drawbacks of complex processes in conventional epitaxially laterally overgrown (ELOG) method, we investigated epitaxy on the patterned insulator on the sapphire substrate (EPISS) method. To optimized growth conditions of a-plane GaN layer the silicon dioxide-patterns, the several shapes and sizes of patterns were considered onto the SiO2 layer. The regular hexagonal patterns of 1 μm window and 6 μm mask were designed as the result of the optimization process. We achieved fully coalescence and smooth surface of high crystalline quality a-plane GaN layers. The XRC FWHM values were measured as 597 arcsec along c-axis direction and 457 arcsec along the m-axis direction, respectively. Also, we investigated the characteristics of nonpolar a-plane GaN layers using combining EPISS and conventional ELOG method. The first (on r-plane sapphire) and second (on a-plane GaN) SiO2 mask were fabricated in the different location to effectively prevent TDs from the window area of the first SiO2 mask. To achieve fully coalesced a-plane GaN layer using combining EPISS and conventional ELOG method, a 10 um thick a-plane GaN layer was grown on EPISS and a 4 um thick a-plane GaN layer was regrowth on the second SiO2 mask to obtain coalescence. The propagated TDs from the window area of the first SiO2 mask was clearly prevented under the second SiO2 mask area. Even though the combining EPISS and conventional ELOG method effectively prevented the TDs in window area, very thick GaN layers were grown to obtain fully coalesced a-plane GaN layer.

To easily obtain a fully coalesced a-plane GaN layer using SiO2 mask, we investigated nanoscale SiO2 mask instead of microscale SiO2 mask. The a-plane GaN layer using nanoscale mask method reduced half of thickness to obtain the full coalescence in comparison with microscale SiO2 mask. Nonpolar a-plane GaN layers with nanoscale SiO2 mask obtained high crystalline quality, PL intensity, surface smoothness, and low pits density as the microscale SiO2 mask method. In this part, we investigated the direct and accurate measurement of the MQW internal quantum efficiency (IQE) using the planar, Single nano mask, and Double nano mask samples. Comparing with the planar and Single nano mask, the Double nano mask showed the best optical properties in terms of optical reflection and scattering at the interface between the a-plane GaN and nanoscale voids. The interfaces of the MQWs on the Double nano mask were abrupt with a large number of distinct satellite peaks. The measured IQE of the Double nano mask was as high as 71 %. This implies that the growth of a-plane GaN MQWs using the double nanopillar SiO2 mask can decrease the numbers of nonradiative recombination centers in the MQWs by reducting the numbers of defects in the epilayer.

Although nonpolar a-plane GaN layer grown by Micro-, and Nanosclae ELOG methods has a low defect density in the wing area (on the mask), the window area (where these is no mask) still has a high defect density. The high density of TDs in the window area can act as nonradiative recombination centers in multiple-quantum wells (MQWs) and decrease the LED device performance. To obvercome these problems, we investigated a new method. Nonpolar a-plane GaN layers with the low overall defect density were grown on r-plane sapphire substrates using a pulse NH3 interrupted etching process. The mixture was injected for 10 sec for slow etching, then the NH3 flow was interrupted for 9 sec for fast etching. This was repeated 50 times in the initial etching of the a-plane GaN layer. Then, the a-plane GaN layer was sequentially etched for 30 min in the mixed NH3 and H2 flow to obtain a deeply etched a-plane GaN layer. The etched a-plane GaN layer with an irregular shape after pulse NH3 interrupted etching in the mixed NH3 and H2 flow. After regowth GaN layer, the upper area in which mass transport occurred clearly has a low TD density. Also, the light output power of LEDs can be increased via light scattering and reflection at the interface between voids and an a-plane GaN layer. LED device based on an a-plane GaN layer subjected to pulse NH3 interrupted etching had higher performance than a planar LED device owing to light scattering and the reduced number of nonradiative recombination centers in the MQWs.

This is very interesting and simple method to overall reduce TDs density. Therefore, semipolar (11-22) GaN, which also can overcome the quantum-confined Stack effect, will be grown on m-plane (1-100) sapphire substrates using pulse NH3 interrupted etching in the future studies.

The characteristic of Ohmic contact of nonpolar p-type a-plane GaN layers was investigated. 1 um thick Mg-doped p-type GaN layer was prepared at 950 ° C. It is well known that Ohmic contact of nonpolar p-type a-plane GaN layers is still challenging task. Because polar and nonpolar p-type GaN layer can obtain Ohmic contact by using a metal with a work function that is higher than 4.5 and 7 eV, respectively. However, no metal has a work function larger than 7 eV.

To overcome these problems, we approached Ni/Au/ITO metallization. Ni (5 nm)/Au (5 nm)/ITO (100 nm) contacts were deposited on nonpolar p-type GaN layers to obtain high transparent and Ohmic contact. The samples were annealed at 500 ° C to 600 ° C in oxygen ambient at 5 min. When the sample was annealed at 500 ° C, we obtained most closed Ohmic behavior.

The specific contact resistance was 7 × 10 ^ -1 Ω cm ^ 2 along c-axis and 2 × 10 ^ -2 Ω cm ^ 2 along m-axis. The measured transmittance at 490 nm was 7.8 % and 89 % for as-dep and annealed, respectively.

The sample was analyzed by XPS measurements. As-dep and annealed samples had layers of Au0 and Ni beneath the ITO cap layer; however, significant differences were observed between the samples. On the as-dep sample the Au layer existed between the ITO and Ni layers. However, Both the Au and Ni layers were thicker on the annealed sample compared to as-dep. In the case of annealed sample, nickel was found as a combination of Ni-oxides and Ni0 and the interface with ITO. As the levels of Ni fell, only Ni0 was observed. The total oxide layer was thicker on the annealed sample in good agreement with the observation of NiOx on that sample.

Very low levels of GaOx were found at the Ni/GaN interface on the as-dep sample. Higher levels of GaOx (relative to GaN) were found at the metal/GaN interface on the annealed sample. This is in good agreement with both the higher levels and deeper penetration of O on that sample.

In this chapter, we demonstrated possibility of Ohmic contact of nonpolar p-type a-plane GaN layer, even though nonpolar p-type a-plane GaN layer could not obtain perfect Ohmic contact and low specific contact resistance in compared with conventional polar c-plane p-type GaN layers. Therefore, the Ni/Au-based metal with TCO contacts will deeply be studied in the future of work.