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主　論　文　の　要　旨

論文題目　**Study on growth of Ga-polar untwinned semi-polar (10-13) GaN templates and (10-13) InGaN/GaN quantum wells**
(Ga 極性非双晶半極性面（10 - 13）GaN テンプレート及び（10 - 13）InGaN／GaN 量子井戸構造の成長に関する研究)

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論　文　内　容　の　要　旨

Nitride semiconductor based blue LEDs have reached very high efficiencies. However, the efficiencies drop fast towards longer wavelengths, the so-called "Green gap". Polarization induced electrical fields along [0001] are thought as the main reason. To overcome this, semi-polar and non-polar orientations have been studied which feature lower fields. Still until now, semi-polar LEDs have lower efficiencies than common (0001) oriented LEDs.

Almost the studied semi-polar LEDs in literatures have negative polarization induced fields, which can cause leaking holes states. This work focusses on the (10-13) orientation, which has a positive field and thus in theory stronger confined hole states. Since almost no previous literature exist on the (10-13) orientation, this work focusses first on making high-quality (10-13) GaN templates and the growth of high indium containing (10-13) InGaN/GaN quantum well on these templates.

The first step is the (10-13) GaN template. Ga-polar untwinned was realized previously on (100) Si substrates by directional sputtering, followed by metal-organic vapor phase epitaxy (MOVPE) growth. However, (10-13) AlN or GaN is not well lattice matched to (100) Si substrates, but it can match well with m-plane lattice well. The mismatch of (10-13) AlN to m-plane sapphire is just -0.8% along $[11\text{-}20]_{sapp}//[30\text{-}3\text{-}2]_{AlN}$ and +4.7% along $[0001]_{sapp}//[11\text{-}20]_{AlN}$. Therefore, the first improvement of this work is to use m-plane sapphire substrates. The directional sputtering suppresses also the formation of twins, which would form if deposit directly on m-plane sapphire. Directional sputtering means that the [1-210] (a-direction) of m-plane sapphire is always pointing towards target. There are two steps in directional sputtering.

The first step is Al sputtering. It only lasts a few seconds but it decides the orientation of the following AlN and GaN layer. By increasing time of Al sputtering, (10-10), (10-13), or even (10-14) orientation are obtained. The (10-10) orientation just slightly worse in lattice match to m-plane sapphire than the (10-13) orientation. The difference is that the (10-13) AlN/GaN unit cell spans over two m-plane sapphire surface unit cells while only one is needed for (10-10) AlN/GaN. If there is enough Al to support migration of AlN over two m-plane surface unit cells, then the low energy (10-13) orientation forms. If the Al thickness is increased further, the AlN layer starts to tilt towards [0001] orientation and gradually (101-14) increases. But also sputtering temperature is important. At high temperature, the Al atoms are mobile enough to form clusters to lower their surface energy. Hence there is no enough Al left elsewhere to enhance the AlN migration. The best condition was a layer of 0.6 nm Al sputtered at 300℃.

The second step is the sputtering of AlN. Also during this step the initial Al is largely converted to AlN. Then the sample will loaded to MOVPE and a second AlN layer is grown on it. Doing the AlN wrong will result in a twinned crystal, but its impact on the final quality of the GaN layer is not so big. Annealing of the sputtered layers improves the quality even at 1320°C.

Compared with (0001) GaN, it is hard to get smooth (10-13) GaN. To obtain both high crystalline quality and smooth morphology, a two-step MOVPE growth is used. The first step use conditions to enhance the roughness, since three dimensional (3D) growth to annihilate dislocations and improve crystalline quality. The second step is two dimensional (2D) growth which conditions to smoothen the morphology. By adjusting the growth conditions and growth time, both high crystalline quality and smooth samples (less than 550 arcsec FWHM in X-ray rocking curve and less than 30 nm RMS) were obtained. This are not only very good values for (10-13) GaN, but are also close to the best values for growth on sapphire for semi-polar GaN grown on heterogeneous substrates.

There are very few reports about (10-13) InGaN/GaN quantum wells. Literature indicates low indium incorporation in (10-13) and related surfaces like (10-12). This was solved in this work using higher growth rates for InGaN layer. With high enough growth rates almost the same indium incorporation of (10-13) and (0001) was reached. So far, 17% indium were incorporated. This is 3 times higher than the highest reported value from literature. In addition, these quantum wells are still fully strained. The PL FWHM follow the same trend for (10-13) quantum wells as on (0001), indicating a comparable quality even at higher growth rates.

To conclude, using directional sputtering on m-plane sapphire and MOVPE, good quality (10-13) GaN templates and indium rich InGaN/GaN quantum wells were realized in this work. This lays the foundation towards a green (10-13) LED.