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From the Editor's Desk

It is our pleasure to present this issue of News letter. III-nitrides semiconductor including GaN, InN, AlN, InGaN, AlGaN and AlInGaN are promising materials, covering the spectral range from deep ultraviolet (UV) to infrared, with unique properties suitable for advanced electronic and optoelectronic applications. Remarkable breakthroughs have been achieved in recent years in these materials and devices. These include high-power and high brightness blue-green-white light emitting diodes (LEDs), UV-blue-green laser diodes (LDs), photodetectors, high power amplifiers based on high electron mobility transistors (HEMT) etc.

In 2014, Physics Nobel Prize was awarded jointly to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura for the invention of efficient blue LEDs. This invention has enabled bright and energy-saving white light sources. Despite considerable efforts, the blue LED had remained a challenge for a long time although red and green diodes had been invented in 1960s. The success and inventions on GaN-based LEDs were revolutionary and benefiting for mankind.

Radio frequency (RF) switches based on GaN technology allow for low insertion loss, higher breakdown voltage and higher-bandwidth switches. These switches can be used in automotive applications such as hybrid vehicles. GaN can also be used safely in biomedical applications including implants, blood monitoring as it is nontoxic. This minimizes the risk to both the environment and the patient. Scientists have also created flexible GaN LEDs that can be implanted and used to detect various cancers such as prostate cancer.

In this issue, we present the growth of wide band gap GaN material and its potential applications. We hope that this will help in more general understanding about the fundamental aspects of III-nitride materials. We further invite the members to contribute the scientific writings about semiconductor research and related activities in their organization to this newsletter.

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Executive Committee of SSI

Growth of GaN by MOVPE

GaN has emerged as the important semiconductor after Si and GaAs. This is because of its various properties like wide band gap (3.4 eV), peak saturation velocity (~2.7 × 10^7 cm/sec), high breakdown field (~3.3 MV/cm), good thermal conductivity (1.3 $Wcm^{-1}K^{-1}$) etc. Such properties make GaN and its heterostructures a potential contender for high power and high frequency devices. In the last two and half decades, there has been a tremendous development in the epitaxial growth of GaN. Due to unavailability of large size, high quality native substrate, the growth is carried out on foreign substrates such as sapphire, Si and SiC. Since these substrates have large lattice and thermal expansion coefficient (TEC) mismatch with GaN, therefore epitaxial growth is very challenging. Out of these substrates, SiC is the best choice as it has the lowest lattice-mismatch (~3.9%) and TEC-mismatch (~25%) with GaN. Beside, SiC has high thermal conductivity (3.8 $Wcm^{-1}K^{-1}$) which is beneficial for high power applications. However SiC substrates are very expensive. Si is the most widely used substrate because of its lower price and larger size availability. But Si has large lattice-mismatch (~17%) and TEC-mismatch (~54%) with GaN. Hence, epitaxial growth of GaN on Si is performed by introducing optimized stress mitigating layers to avoid cracking of film during cooling after growth. But due to lower thermal conductivity of Si (1.5 $Wcm^{-1}K^{-1}$), its usage is restricted to low power applications. Sapphire is also a popular choice as its lattice mismatch (~13%) and TEC-mismatch (~34%) with GaN is lower than Si. However, low thermal conductivity of the sapphire substrate (0.42 $Wcm^{-1}K^{-1}$) limits its practical usage mainly to low power optoelectronics devices (LEDs). Molecular beam epitaxy (MBE) and metal organic vapour phase epitaxy (MOVPE) are the two widely used techniques to grow GaN. MOVPE is preferred in industries because of its versatility, larger throughput and commercially economical. In MOVPE, metal organics such as trimethylgallium (TMGa), trimethylaluminium (TMAl) and trimethylindium (TMIn) are used as group-III precursors. These metal organic sources are stored in stainless steel bubblers through which ultra high pure carrier gas (hydrogen or nitrogen) flows. Carrier gas helps to transport the vapors of these precursors to the growth reaction chamber. Ammonia is used as group-V precursors. SiH_4 and Si_2H_6 are used for n-doping while bis (cyclopentadienyl) magnesium is used for p-doping. The temperature required to grow nitrides is generally higher than that of phosphides and arsenides. The epitaxial growth by MOVPE consists of many complex steps including gas phase and surface reactions such as transport of precursors to the reaction chamber, pyrolysis of precursors, adduct formation, diffusion, desorption etc (Figure 1).

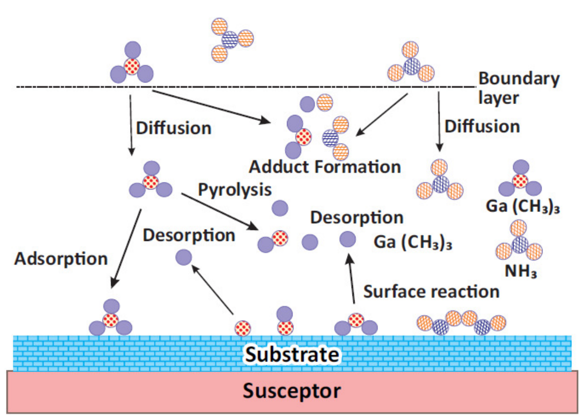

Fig. 1: Schematic of different processes in MOVPE.

On the basis of relationship of growth rate with temperature (T), there are three growth regimes in MOVPE (Figure 2). (a) Kinetic control limited: In this regime, growth rate has strong dependence on temperature; (b) Mass transport limited: Here, the growth rate remains nearly constant w.r.t. temperature; and (c) Desorption control limited: This regime has dominance of parasitic reactions and desorption, thereby growth rate is lower. Generally, mass transport limited is preferred because the growth rate is independent of temperature. For nitride growth, mass transport limited regime, at the onset of desorption limited, is used because of high cracking efficiency of ammonia in this regime. The precise control of growth rate, composition and doping in epilayers is done by adjusting the flow rates of precursors, relative ratio of mole fractions of group-V and group-III precursors. Latest MOVPE systems are equipped with in-situ monitoring tools to provide information of growth related parameters like growth rate, epilayer thickness, wafer curvature etc. These measurements aid in optimization of the growth process.

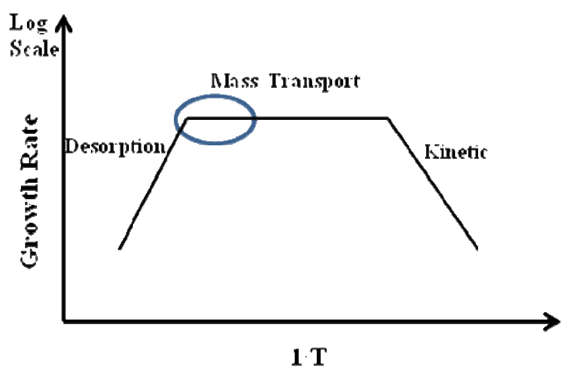

Fig. 2: Variation of growth rate with temperature.

The growth of GaN directly on foreign substrate (sapphire) at high temperature is island growth due to the lattice-mismatch and chemical dissimilarity between epilayer and substrate. So the concept of two steps growth is introduced. In first step, a few nanometers layer called as nucleation layer (NL) is grown at lower temperature. Then the subsequent GaN layer is grown at high temperature in the second step. This two steps process improves the quality of epilayer. By optimizing the growth parameters, density of nucleation sites can be controlled. This results in achieving smoother single crystalline epilayer with reduced dislocation density. Detailed growth mechanism of GaN on sapphire is described below. Figures 3 and 4 show the in-situ reflectance traces along with different stages of GaN growth on sapphire using GaN NL for two different samples (A and B). The growth parameters (flow rates, temperature, pressure, time, V/III ratio etc.) are different for both samples. Initially, sapphire is annealed at high temperature ~1100°C to remove surface contamination. Then a few nanometers of NL is grown at low temperature ~550°C. This follows by annealing at ~1040°C.

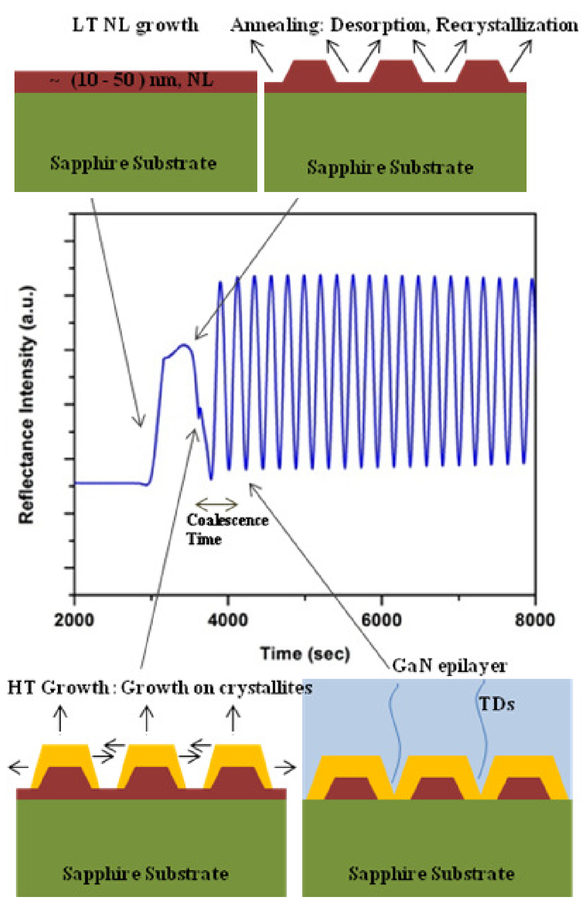

Fig. 3: In-situ reflectance trace along with growth steps (Sample-A).

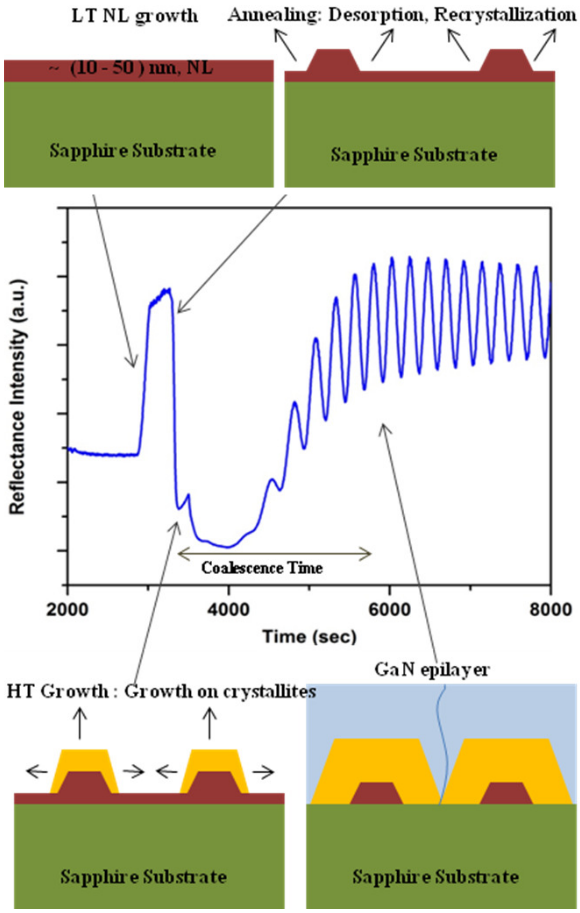

Fig. 4: In-situ reflectance trace along with growth steps (Sample-B).

During annealing, crystallinity of epilayers improve, desorption occurs and islands of GaN form which act as nucleation sites for further growth. At this stage, surface becomes rough because of the formation of islands. This decreases reflectivity due to the increase in scattering of light. Afterward, GaN growth is performed at higher temperature where growth occurs on already formed islands laterally as well as vertically. This leads to the coalescence of islands and layer-by-layer two dimensional (2D) growth occurs. 2D growth can be ascertained from proper Febry-Perot oscillations in in-situ reflectance trace. The coalescence time that is, time needed for the reflectance to fully recover the stable oscillations, is different in both samples. The dislocation density estimated by high resolution X-ray diffraction is more in sample-A. This is because the sample-A has less coalescence time than sample-B. The lesser coalescence time in sample-A is due to larger density of nucleation sites and higher lateral growth rate. It is also observed that sample-A is more resistive than sample-B. To understand this, we should know that as-grown GaN shows n-type conductivity and this may be due to residual impurities. Since threading dislocations (TDs) act as electron traps, therefore higher dislocation density, traps more carriers resulting resistive GaN epilayers. High resistive GaN epilayers are required for transistor applications. The technique to increase TDs by optimizing growth parameters is not only tricky as window to play growth parameters is small but it also degrades the crystalline quality of epilayers. So around the world, researchers have also used acceptor type impurities such as carbon and iron to trap carriers to make GaN epilayers more resistive without degrading their crystalline quality. In summary, using different types of NLs, acceptor type impurities and optimizing growth parameters, single crystalline GaN epilayers of desired conductivity can be grown for electronics or optoelectronics applications.

More information about this can be found from the following references:

[1] H. Amano et al., *Applied Physics Letters*, 48, 353 (1986).
[2] S. M. Hubbard et al., *Journal of Crystal Growth*, 284, 297 (2005).
[3] S. Nakamura, *Japanese Journal of Applied Physics*, 30, L1705 (1991).

Kapil Narang, SSPL, New Delhi

Seminar on "Advances in Compound Semiconductor" on 25th July 2017 at SSPL, Delhi

One day seminar on "Advances in Compound Semiconductors" was organized by Solid State Physics Laboratory (SSPL) in association with Semiconductor Society (India) on 25th July, 2017. It was a very special event as it was organized to felicitate Prof. Vikram Kumar on the occasion of his 70th birthday. Prof. Vikram Kumar was formerly the Director of SSPL, Director of NPL and faculty at IIT Delhi. He is a renowned semiconductor physicist and technologist. He has contributed immensely in advancement of semiconductor physics and devices in India. The technical lectures were delivered by Prof. C. J. Panchal (MSU, Baroda), Prof. Subhashish Ghosh (JNU, New Delhi) and Prof. Rajendra Singh (IIT Delhi). After that, a felicitation ceremony was held to felicitate Prof. Vikram Kumar.

Recent news in semiconductors

1. Researchers at the Arizona State University (USA) claim the first AlN Schottky barrier diodes (SBD) with breakdown more than 1 kV (Houqiang Fu et. al., *IEEE Electron Device Letters*, 38, 1286, 2017). AlN material was grown by MOCVD on single side-polished (0001) sapphire substrate. SBD consists of 1 µm unintentionally doped AlN underlayer, 300 nm Si doped *n*-AlN and 2 nm unintentionally doped GaN cap. The researchers reported narrowest FWHM X-ray peaks for MOCVD AlN-on-sapphire (46.8 arcsec) for the (0002) rocking curve. The temperature dependence of the device performance suggests that the forward current was limited by thermionic emission. SBD height increased from 0.9 to 1.6 eV between RT and 200°C. The ideality factor decreased from 5.5 to 2.2. Previous reported idealities of AlN SBDs have been greater than 8. Under reverse bias, SBDs broke down after 1 kV, beating previous reports of ~700 V for devices produced on free-standing AlN substrate.

2. Researchers in France have created a range of optically pumped III-nitride microdisk lasers on Si covering a wide range of wavelengths. Two types of multiple quantum well structure were produced: GaN wells with AlN barriers (deep UV), and InGaN with GaN barriers (violet and blue-green). The researchers added that the broad tunability paves the way to the development of a UV-visible integrated photonic platform embedding microlasers, possibly addressing multiple wavelengths. A further step will deal with the electrical injection, following the recent progresses in electrically injected InGaN lasers on Si-substrates. In the case of visible-UV devices, potential applications include bio-chemical analysis and on-chip optical interconnects (J. Sellés et al., *Applied Physics Letters*, 109, 231101, 2016).