Gallium Nitride Crystal Growth In Situ Monitoring Techniques

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We present a novel *In Situ* monitoring technique for the growth of gallium nitride based materials and device structures. Using the bulk transmission characteristics of GaN, the temperature dependency of the band-edge is analyzed to extract key parameters which can be used for quality control in Light Emitting Diode (LED) production. Results obtained from a LED structure growth process demonstrate the potential of the technique for precise wafer temperature measurement compared to traditional pyrometry systems, which measure the temperature of the substrate below the infrared-transparent wafer. Using a time-correlated single wavelength band-edge transmission approach, a highly reproducible temperature measurement of the wafer surface was obtained. Further, precise determination of the surface residual roughness during the initial phase of the growth, or pit density, was precisely monitored in a quantitative fashion. Finally, effects of the Indium incorporation in multiple quantum well (MQW) structures used in optical emitting devices was measured to unprecedented detail. Further analysis of this information should lead to real-time monitoring of the Indium concentration, in turn bringing a new level of precision to the epitaxial deposition process of GaN based materials.

1. Introduction

In manufacturing, obtaining real time feedback of the process is important in order both to determine problems at early stages as well as to optimize the throughput of production. In the case of LEDs as well as most semiconductor based device fabrication, the initial process and the semiconductor wafer growth process can be considered most crucial. Maximizing the within-wafer (WIW) uniformity, minimize wafer defect density, and control the emission wavelength of the resulting LED, all depends on the crystal growth quality control. *In situ* monitoring tools providing real time measurements of the process are more and more being seen as basic necessity for this purpose. A particular important parameter to optimize is the temperature at the wafer surface before performing the active layer of the LED (MQW) in order to control the final emission wavelength. Traditionally, *In Situ* temperature measurements are based on an optical pyrometry system which measures the amount of black body emission. To further improve the accuracy of pyrometric measurements, such system usually have to be corrected for emissivity changes at the surface of the thin film.[1,2] However, a fundamental remaining problem is that such systems cannot distinguish between a lowering of the temperature and an unrelated decrease in the measured emission intensity such as due to a dirty window on the growth chamber. Furthermore, in the common case of GaN based LEDs grown on sapphire, where the material is transparent in the near-infrared (NIR), most of the black body emission seen by optical pyrometry comes from the heated susceptor behind the actual wafer.[6] In order for pyrometry to be effective in measuring the wafer temperature of GaN on Sapphire, the measurement would need to be made in the non-transparent region of the spectrum, typically at wavelengths shorter than 400nm.[9] This in turn has the disadvantage that black body emission decreases exponentially toward shorter wavelengths and nearly no photons are emitted at temperatures near the ones critical to the process. In this paper, we introduce a novel method allowing absolute measurement of the wafer surface temperature. This method is based on the time-correlation of a single transmitted wavelength near the band-edge of GaN, allows for rapid measurement (μsec sampling) even at low temperature, and is emissivity independent. Furthermore, due to the nature of this measurement not depending directly on emission intensity[5], traditional pyrometry may be calibrated by this

Figure 1: YGrowthMonitor (YGM) family product

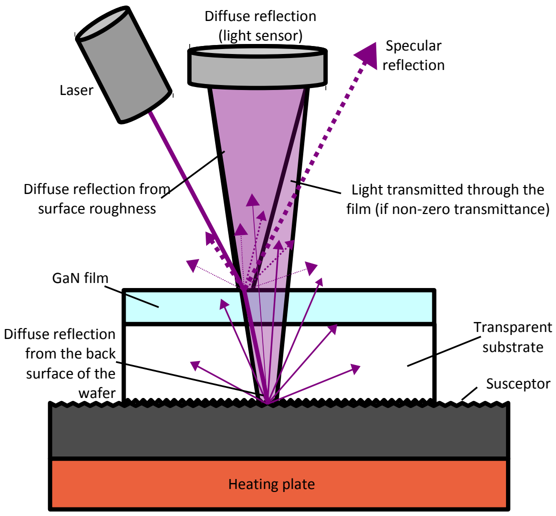

Figure 2: YGM-BandTime schematic diagram

method. Systems using only pyrometry for temperature determination require frequent calibrations to compensate for changes in the intervening optical components (such as window of the port chamber, or any optics required to access the chamber).[4,5,6] Exploiting the band-edge characteristic has the big advantage of being able to obtain a measurement of the temperature without any required calibration procedure. This new technology has been integrated in the latest generation of YGrowthMonitor(tm) tools, a family of *In Situ* monitoring products built by YSystems. Figure 1 shows an example research level system which includes the YGM-BandTime(tm)[7,8] module making use of the technology discussed in this paper.

2. Method

Figure 2 shows the principle behind YGM-BandTime. The incident light on the wafer is first transmitted through the thin film, and then reflected by the rough back surface of the substrate and/or the susceptor surface. The diffused reflection is collected by a sensor placed at a different angle compared to the specular reflection. When temperature of the GaN layer increases, its band-edge transmission characteristic shifts to longer wavelength, as shown in Figure 3. The band-edge transmission is directly related to the bulk temperature of the GaN epitaxial layer, and therefore it is possible to extract an absolute temperature value of the wafer surface. An important point is that the diffuse reflectance used is independent from the emissivity changes of the substrate surface.[3] Furthermore, using single monochromatic laser light (single wavelengths) allows for rapid monitoring, even at low temperature, compared to full spectral acquisition, or compared to long light integration times that would be required to acquire black body emission signals at short wavelengths.[6] As mentioned above, in order to detect pyrometric information at the wafer surface, measurements made in the near ultra-violet portion of the spectrum have to be performed, since the GaN becomes transparent at longer wavelength. In spectral acquisition, white light or broad band emission light sources are usually used. Due to the large amount of data required to obtain a spectrum, and due to the relatively weak signal as compared to laser light, it is technically difficult to make such a measurement in microsecond time scales. The method presented here doesn't suffer from these drawbacks.

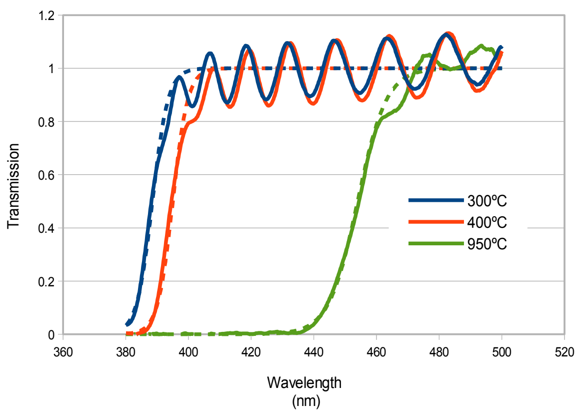

Figure 3: Temperature dependence of the GaN transmission spectrum

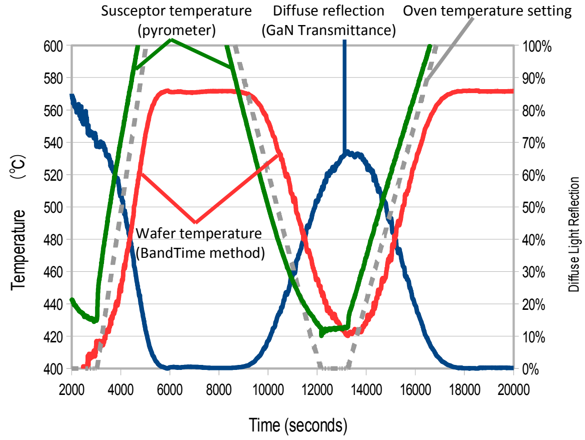

Figure 4: Pyrometer temperature versus wafer temperature for GaN on sapphire

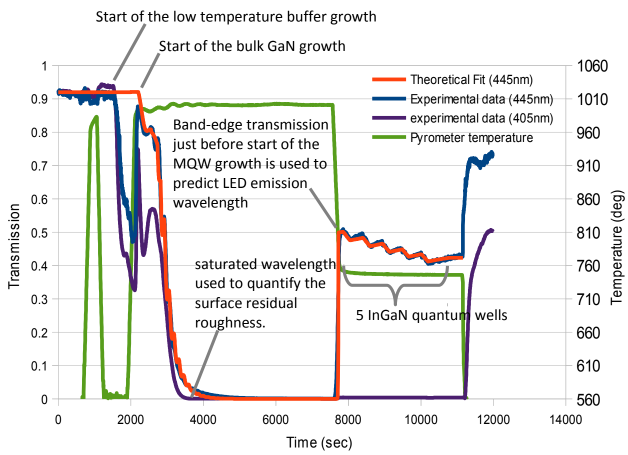

Figure 5: YGM-BandTime growth monitoring

High power blue lasers are used, making the reflected signal easy to distinguish from the background radiation of the heater. As each individual wavelength is specific to a certain temperature range, multiple wavelengths (lasers) are used to cover a wide range of temperatures.

3. Results

Measurements made of a GaN/Sapphire wafer in a controlled radiative oven are shown in Figure 4. For this experiment, the wafer was placed on a quartz susceptor. Wafer surface temperature has been extracted using the band-edge transmission of GaN to demonstrate how important can be the difference between the susceptor temperature measured by a pyrometer and the wafer temperature. Those measurements have also been made at low temperature, illustrating the capacity of this method to monitor low temperature processes. With the collaboration of the university of Nagoya, *In Situ* monitoring of a LED structure grown by metal-organic chemical vapor epitaxy (MOCVD) had been measured using YGM-BandTime. Results obtained are illustrated in Figure 5. The GaN transmission for two different wavelengths are shown (405nm and 445nm). In this process, the shortest wavelength is used to quantify the surface roughness, as it will be explained in the next section. The 445nm band-edge transmission is used to obtained the absolute temperature at the wafer surface. Another interesting aspect is the result obtained while performing the MQWs. Variations observed in the transmission signal are directly correlated with the deposition process of indium, and will also be discussed further below.

4. Discussion

For GaN layers above a certain thickness, wavelengths below the transmission band-edge (called here "saturated wavelength") will result in technically 0% of the source being reflected from the back of the wafer. The only remaining signal is therefore a diffused reflection from the wafer surface, as shown in Figure 2. By monitoring the diffuse portion of this reflection, information about the surface roughness can be obtained. In the initial phase of the growth, a high density of pits are present at the wafer surface, resulting in a strong diffused reflection. As the growth progresses, pit density reduces, and consequently the surface roughness induced signal gradually disappears, as it can be seen in Figure 5. The time at which the saturated wavelength becomes flat is used to precisely quantify the surface residual roughness, or the complete overgrowth of pits. Knowing this precisely can be used to greatly improve the efficiency of LED growth as most of the process time is currently being used to guarantee a complete GaN buffer layer. The thickness of this layer can be optimized *In Situ* if the time required to form the complete epitaxial layer is known.

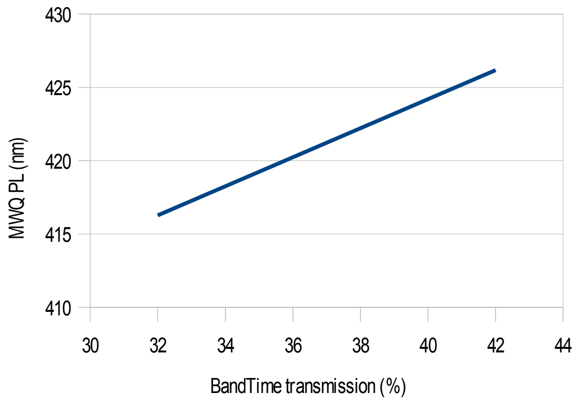

Figure 6: MQW PL trend vs GaN transmission band-edge @ 445nm

Another important parameter for LED production is the absolute temperature at the wafer surface when growing the Indium containing active layer of the LED. The temperature during this process is very important since it will directly affect the indium incorporation during the deposition process. The final indium composition of a LED in turn determines its emission wavelength. Using traditional pyrometry system, it is impossible to get an absolute temperature, since pyrometer measures the susceptor temperature. As shown in Figure 4, there is a considerable difference between the susceptor temperature and the temperature at the wafer surface. Pyrometer measurements are also affected by the transmission changes of optical components in its field of view, and therefore increase the difficulty of obtaining accurate and reproducible information. With the BandTime technology, there is no such problem since the band-edge characteristic is independent of the light intensity. Highly reproducible temperature measurement from one process to another can be achieved. As the band-edge transmission of the GaN is directly related to temperature, the LED emission wavelength can be said to be dictated by the bulk band-edge transmission. The dependence of the

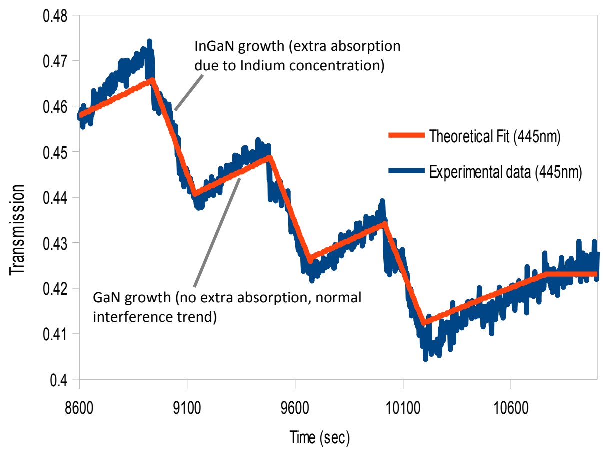

Figure 7: InGaN quantum wells growth

LED emission wavelength as function of bulk transmission, or BandTime temperature, has been observed and the trend obtained is shown in Figure 6. From this trend, a direct reading of the band-edge transmission just before the start of the MQW growth (as illustrated in Figure 5) enables the prediction of the final LED emission wavelength.

Finally, details of the growth monitoring during the MQW structure warrant further discussion. Figure 7 shows a blow-up of this section taken from Figure 5, where the impact of the indium deposition on the transmitted signal is clearly seen. Each phase of the process can be observed, wherein for each step of InGaN deposition the absorption is seen to increase, while in each step of the GaN barrier the absorption remains constant, except for the optical interference change due to the layer thickness changes. The degree of absorption caused by the indium deposition gives unprecedented information related to each quantum well. Theoretical fitting has been performed and results obtained so far show great potential for exploiting this information

5. Conclusions

In the present paper, we have introduced YGM-BandTime, a new generation *In Situ* monitoring technology based on time-correlated single wavelength band-edge transmission. The temperature dependence of the band-edge is used to infer the wafer temperature, promising enhanced quality control for LED production. This technology enables rapid measurement of the absolute temperature of the wafer, even at low temperature. As the band-edge characteristic is independent of the light intensity, no particular calibration process is required, as opposed to traditional pyrometric system, which are affected by the transmission changes of intervening optical components. Highly reproducible temperature measurement of the wafer surface was achieved. Furthermore, use of saturated wavelengths was shown to provide information on the surface residual roughness during the initial phase of the growth. Finally, results obtained during the MQW process showed unprecedented detail, in which we could distinguish each phase of the indium deposition process. Those results demonstrate a great potential in a new avenue of monitoring epitaxial deposition process of GaN based materials.

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