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UV LED System for PL Measurements on GaN Samples

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Gallium Nitride materials are direct bandgap semiconductors with important applications, such as in the production of light-emitting diodes and transistors. The process of photoluminescence, in which excited electron and holes emit electro-magnetic radiation when they recombine, can be used to study the structure and quality of Gallium Nitride materials. Due to the size of the bandgap in these materials (3.4eV), ultraviolet light is required to create electron-hole pairs in GaN. We designed and built a system, which uses ultraviolet light, to take measurements on GaN samples provided by a local company, Lightwave Photonics, who were interested in the quality of the materials they develop and produce. Our system uses a ultraviolet LED as a light source instead of an expensive UV laser. It uses two short-pass filters and a long-pass filter to isolate the luminescence from the sample from excitation source. A spectrometer measures intensity of the luminescence versus wavelength. A camera is also used to observe the samples during set-up. The system was calibrated using radiation from a black-body source. We were able to take measurements on several samples. Our results agree with the expected emission spectra of GaN materials.

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UV LED System for Photoluminescence Measurements on GaN Samples

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Abstract

Gallium Nitride materials are direct bandgap semiconductors with important applications, such as in the production of light-emitting diodes and transistors. The process of photoluminescence, in which excited electron and holes emit electro-magnetic radiation when they recombine, can be used to study the structure and quality of Gallium Nitride materials. Due to the size of the bandgap in these materials (3.4eV), ultraviolet light is required to create electron-hole pairs in GaN. We designed and built a system, which uses ultraviolet light, to take measurements on GaN samples provided by a local company, Lightwave Photonics, who were interested in the quality of the materials they develop and produce. Our system uses a ultraviolet LED as a light source instead of an expensive UV laser. It uses two short-pass filters and a long-pass filter to isolate the luminescence from the sample from excitation source. A spectrometer measures intensity of the luminescence versus wavelength. A camera is also used to observe the samples during set-up. The system was calibrated using radiation from a black-body source. We were able to take measurements on several samples. Our results agree with the expected emission spectra of GaN materials.

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1 Introduction

One of the most important families of semiconductor materials includes binary compounds, such as Aluminum Nitride (AlN), Indium Nitride (InN), Gallium Nitride (GaN), and their alloys. All of these materials are direct bandgap semiconductors with varying sizes of their energy gap from 0.7 eV for InN to 3.44 eV for GaN. Their properties make them suitable for a wide range of applications, including the production of UV LED's and lasers, photovoltaic solar cells, and transistors used in high-voltage, high-temperature, and high-power operation. In particular, GaN exhibits properties such as durability, high thermal conductivity, and piezoelectricity, which make it well-suited for the production of some of these devices.

Lightwave Photonics is a local company which develops and produces GaN-related materials and devices. They use a physical vapour deposition method of production, called sputtering, in which a thin film is deposited onto a substrate, such as sapphire, via sputtering material from a target. They were interested in using photoluminescence spectroscopy to study the quality of the materials they produce. Light in the ultraviolet range is required for performing photoluminescence measurements on GaN due to the large size of the energy bandgap of the material. Conventionally such measurements are performed using a UV laser as a light source. However, UV lasers are very expensive, thus we designed and built a system for performing the measurements using a UV LED as a light source instead.

Our system uses a UV LED, two short-pass filters, a dichroic beamsplitter, several lenses, a mirror, and a spectrometer for measuring the spectra of the samples. Due to the varying sensitivity of the spectrometer, depending on the wavelength of incident light, the system had to be calibrated. We used LabView software to create a calibration program, which is based on measurements we performed on a light source of a known spectrum (quartz-halogen light bulb). This program was used to calibrate the spectra we measured. We were able to obtain meaningful measurements of the sample spectra. Our measurements show the expected GaN-related luminescence at around 360 nm. We also measured some yellow luminescence at wavelength around 500-600 nm, which is typically seen in GaN materials. This luminescence is due to defects in the material, and although its origin is debated between scientists, it is most often attributed to gallium vacancy-related defects or carbon-related defects. It is unclear what caused the yellow luminescence in the Lightwave Photonics samples, however, the spectra we obtained suggest that our system is suitable for performing measurements on GaN materials.

2 Background

2.1 Gallium Nitride Materials

2.1.1 Structure and Properties

Gallium Nitride is a III-V semiconductor with Wurtzite crystal structure, which is common in semiconductors, and a direct bandgap of 3.44 eV, that is, the energy difference between the conduction band and the valence band in the material is 3.44 eV. Figure 1 shows the size of the bandgap of GaN compared to other nitride semiconductors. The atoms in GaN are arranged in a hexagonal array structure, with covalent bonds between them. Gallium Nitride is a mechanically stable, durable material with high heat capacity and thermal conductivity. It can be doped with different materials, such as Silicon and Germanium to be n-type, and Magnesium to be p-type. Commercially Gallium Nitride is most commonly produced using molecular beam epitaxy in which a thin film is deposited onto a bulk substrate, such as sapphire.

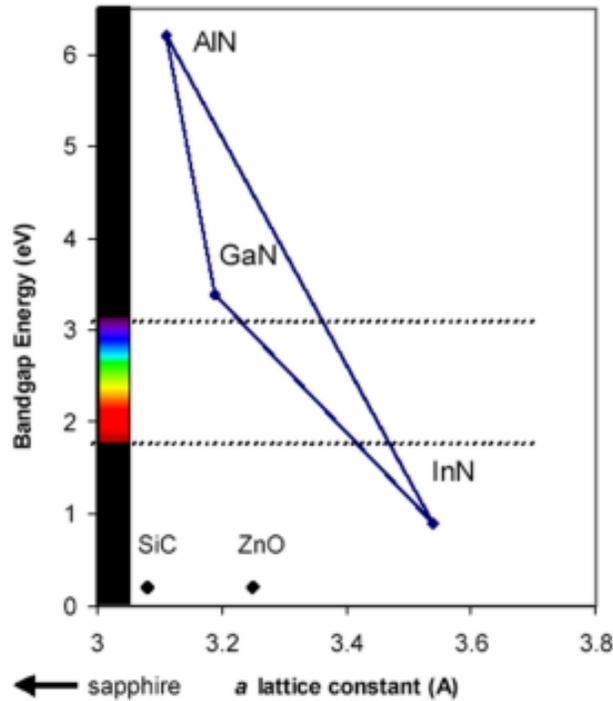


Figure 1: Schematic of energy bandgap versus lattice constant

2.1.2 Applications

Most of the important applications of Gallium Nitride depend on the large size of its bandgap, which makes it suitable for the production of optical devices in the visible short wavelength range. Because of its large bandgap, Gallium Nitride is used in combination with other materials, such as Aluminium and Indium, to produce LED's which can emit light of a wide range of wavelengths, from ultraviolet to red light. The wavelength of the emitted light depends on the amount of doping material introduced into the GaN.

Some of the other properties of Gallium Nitride, namely its durability, high conductivity and heat capacity, make it desirable in the production of transistors which are used in high-voltage, high-temperature applications. GaN transistors are suitable for applications which require operating at high-voltages with high efficiency, for instance, aerospace and wireless infrastructure applications.

In addition, InGaN, one of the derivatives of GaN, is suitable for the production of solar photovoltaic cells.

2.2 Photoluminescence

Photoluminescence is the process in which a material emits light after absorbing photons. It exploits the energy gap between the valence and conduction bands in solids. In the process of photoluminescence, a material is exposed to electromagnetic radiation. Electrons in the valence band absorb the energy of the electro-magnetic radiation, and transfer to the conduction band, leaving behind vacancies, referred to as holes, which behave like positive charges. When in the conduction band, the excited electrons lose energy by re-emitting some of the absorbed radiation and recombine with the holes in the valence band. This process is illustrated in Figure 2.

The excitation of electrons in different materials requires electro-magnetic radiation of different frequencies, depending on the size of the bandgap of the material. In order for electrons to be excited from the valence band, the material has to be exposed to electro-magnetic radiation with energy equal to or greater than its bandgap. The time between absorption and emission also varies depending on the material. In Gallium Nitride it is of the order of nanoseconds.

Photoluminescence can be used to characterize the quality and properties of materials. In photoluminescence spectroscopy, light with photon energy greater than the energy of the material bandgap is shined onto a material, and the emission spectrum is recorded. The energy of the emitted light depends on the properties of the material, thus the emission spectrum can be used to detect impurities and defects. When defects are present in the material, they form defect levels, which capture electrons during recombination. This causes the emission of radiation of different wavelengths, as shown in Figure 3. Common defects in GaN produce luminescence in the yellow range.

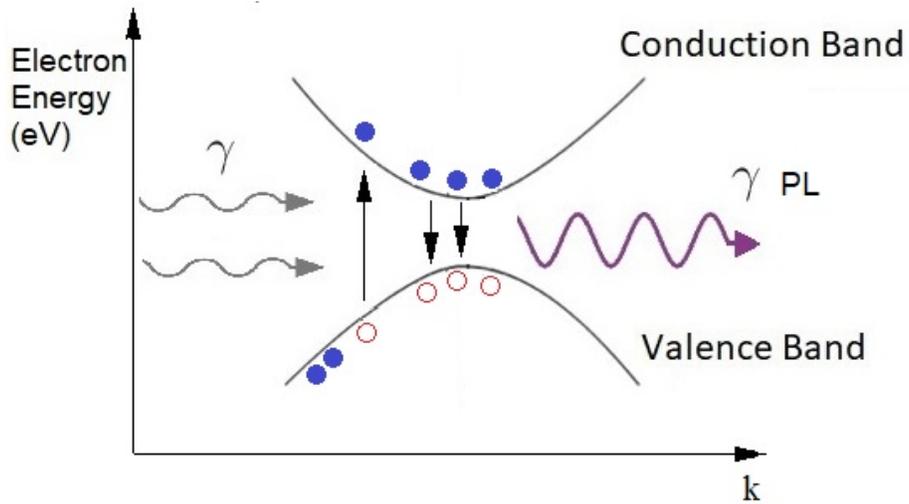


Figure 2: Schematic of the process of photoluminescence

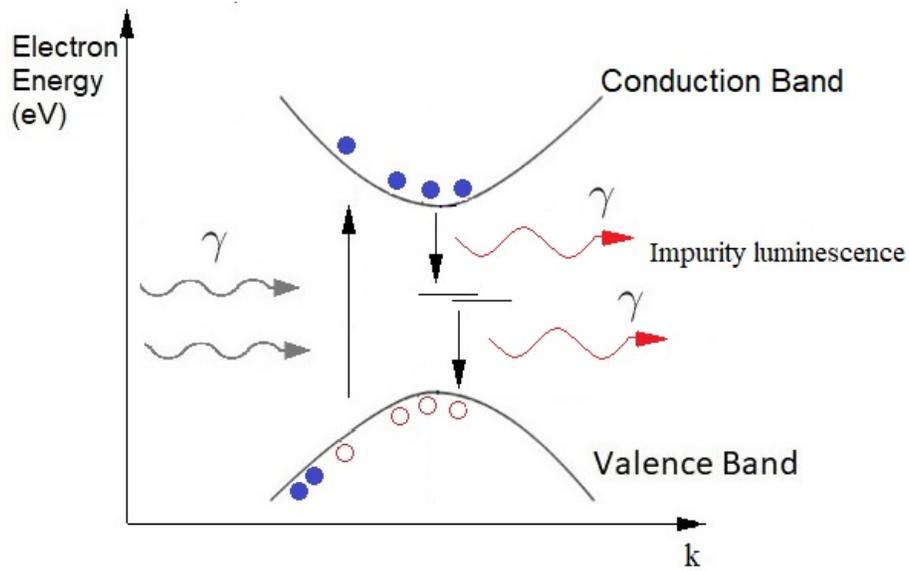


Figure 3: Schematic of the process of photoluminescence caused by impurities

3 The System

As stated before, the frequency of the electro-magnetic radiation necessary to excite electrons from the conduction to the valence band depends on the material. Due to its large bandgap, GaN requires ultraviolet radiation in order for electrons to be excited, hence the system we built uses a UV LED as its light source. It also uses two CaFl lenses, a short-pass filter, a colored filter, a dichroic mirror, a right-angle prism mirror, a UV SiO_2 lens, a camera, and a spectrometer which is a Spectra Pro 300i spectrograph fitted with ST-1603ME CCD camera from Santa Barbara Instrument Group.

3.1 Design

The schematic of the system is shown in Figure 4. The UV LED is mounted onto a 2.54 cm lens tube using a coupler. Inside the tube, at a distance around 9 mm from its end, we placed one of the CaFl lenses. The short-pass filter was also placed in the tube, around 10 mm away from the lens. The colored filter was mounted in the same tube after the short-pass filter. We placed another CaFl lens in a tube directly above the sample, around 2.5 cm away from it. The dichroic beamsplitter (mirror) was mounted in a cubic cage above the lens. The right-angle prism mirror was mounted in another cubic cage 2.5 cm above the beamsplitter. The hypotenuse of the prism mirror has a reflective metallic coating of UV enhanced Aluminum which allows it to reflect incident light beams at 90 degrees. Above the prism mirror we placed the CCD camera. We mounted the UV SiO_2 lens, with focal length of 50 mm, in a lens tube around 5 cm away from the prism mirror. We placed another lens tube between the UV lens and the slit of the spectrometer.

The LED we used emits 40 mW of UV light at 300 nm. The first CaFl lens, which has focal length of 40 mm, collimates the light from the LED onto the short-pass filter, which transmits light with wavelength between 250 and 321.5 nm and blocks light with wavelength above 330 nm. In the original design of the system the short-pass filter was used by itself, however, we found that it allows some light of longer wavelength to leak through. Thus, we added the colored glass filter which cuts off light of wavelength larger than 370 nm. The transmittance of the two short-pass filters as a function of wavelength is shown in Figure 5. The dichroic beamsplitter we used acts as a long-pass filter. It reflects light of wavelengths between 300 and 325 nm and transmits light of wavelengths between 326 and 1200 nm. Its transmittance as a function of wavelength is shown in Figure 6. Light with wavelength between 300 and 325 nm is reflected downwards onto the second CaFl lens, which focuses it onto the sample. After absorbing the radiation, the sample emits light of longer wavelength, to which the beamsplitter is transparent. The emitted light is reflected by the prism mirror, and focused onto the slit of the spectrometer by the UV lens. The CCD camera is used to observe the sample and to adjust the distance between it and the CaFl lens above it. Before taking a measurement, the height of the sample holder was adjusted until we were able to see a focused image of its features with the camera.

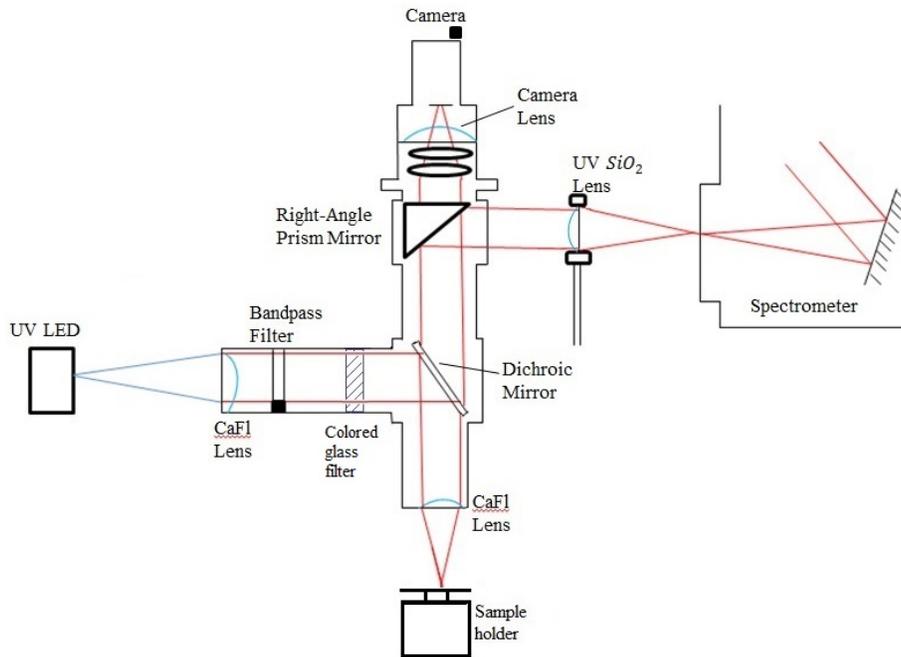


Figure 4: System Schematic

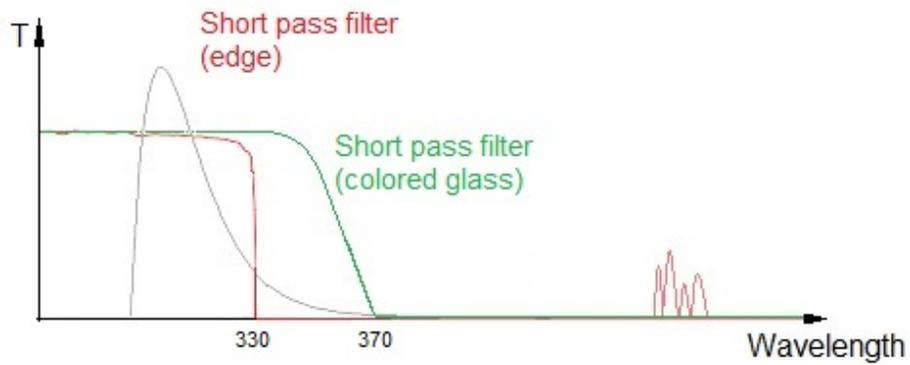


Figure 5: Schematic of transmittance of short-pass filters

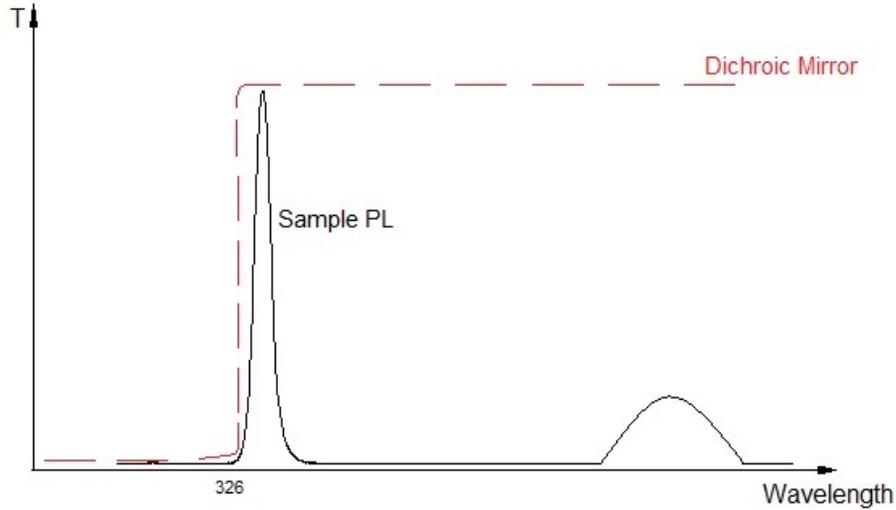


Figure 6: Schematic of transmittance of dichroic mirror

3.2 Calibration

After taking measurements on our GaN samples, we obtained a graph of raw intensity as a function of wavelength. The sensitivity of the spectrometer used to collect the emission spectra depends on the wavelength of incident light, thus the measurements we took had to be corrected to account for this wavelength dependence. In order to calibrate our system, we took measurements on a source whose spectrum is already known and used it to correct the intensity at different wavelengths.

The known source we used was a quartz-halogen light bulb, whose spectrum is that of a black body at 3500 K. We created a LabView program which graphs the intensity of a black body in terms of wavelength and temperature using Equation 1:

$$I(\lambda, T) = \frac{A}{\lambda^5} \times \frac{1}{e^{\frac{B}{\lambda T}} - 1}, \quad (1)$$

where $A = 2hc^2$ and $B = \frac{hc}{k}$. We took a measurement of the spectrum emitted by the quartz-halogen light bulb and divided the collected signal data by the intensity values of the black body curve, which is how we obtained the sensitivity function $S(\lambda)$:

$$S(\lambda) = \frac{\text{Measured Signal}}{\text{BB Signal}} \quad (2)$$

$S(\lambda)$ is a function of wavelength, which tells us how much we need to correct the raw intensity measurements at each wavelength. The corrected intensity as a function of wavelength is obtained by dividing the raw intensity by the sensitivity factor.

Figure 7 below shows the graph of the emission spectrum of a black body at 3500 (white curve) and the emission spectrum we measured from the quartz-halogen light bulb (red curve). The sensitivity function is shown in Figure 8.

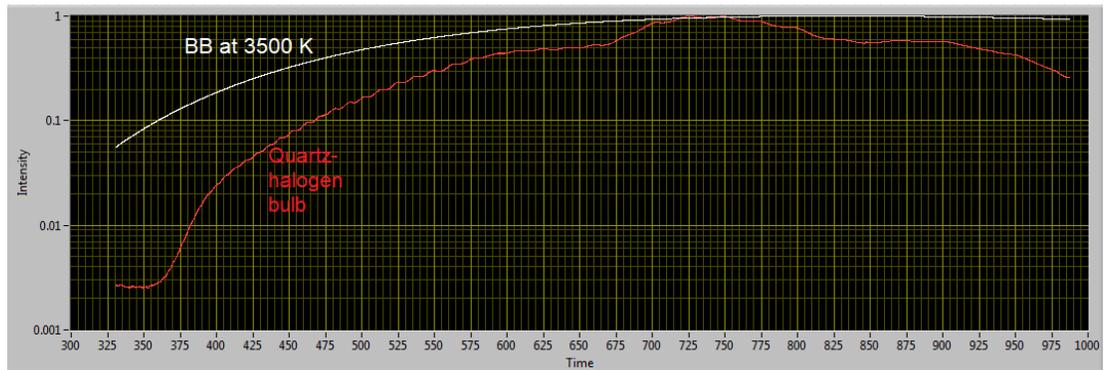


Figure 7: Measured signal vs Black-body signal

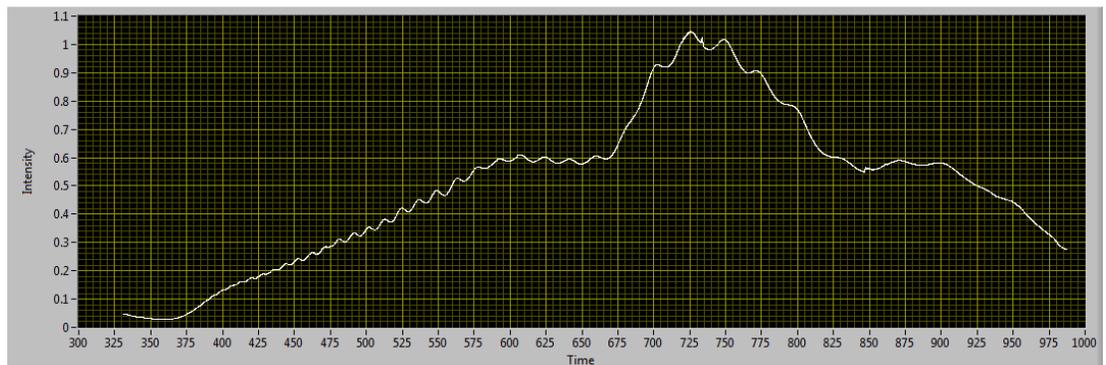


Figure 8: Sensitivity function

4 Results

We took measurements on several samples of Gallium Nitride materials, provided to us by Lightwave Photonics. Figures 9 and 10 below show measurements of raw intensity as a function of wavelength for a sample of undoped (intrinsic) GaN and a sample of n-type GaN.

The peak wavelength of the emitted radiation can be calculated using Equation 3:

$$\lambda = \frac{hc}{E} \quad (3)$$

Given the bandgap energy of 3.44 eV, we expect an emission peak at 360 nm. As expected, we observed a peak in the GaN luminescence at about 360 nm for both the intrinsic and the n-type material.

The intensity of the luminescence is proportional to the product of the electron and hole densities. When GaN is doped to be n-type, electrons are introduced into the material. The n-type GaN samples contain more electrons, hence the density of electrons in the n-type GaN is higher than that in the intrinsic GaN samples. Thus, the luminescence at 360 nm is stronger in the n-type GaN.

We used the sensitivity function to calibrate our measurements. The plots of calibrated intensity as a function of wavelength for the intrinsic GaN and the n-type GaN are shown in Figure 11 and Figure 12. The peaks at 360 nm are due to luminescence from GaN. Additionally, we observe a broad yellow luminescence band at around 500-600 nm. Yellow luminescence, caused by defects in the material, is commonly observed in GaN. Its exact origin remains unclear, however, it is believed to be caused by gallium vacancy-related defects or carbon-related defects. We have not been able to identify the source of the yellow luminescence in our GaN samples, however, the spectra we obtained show that our system is suitable for doing photoluminescence spectroscopy on GaN.

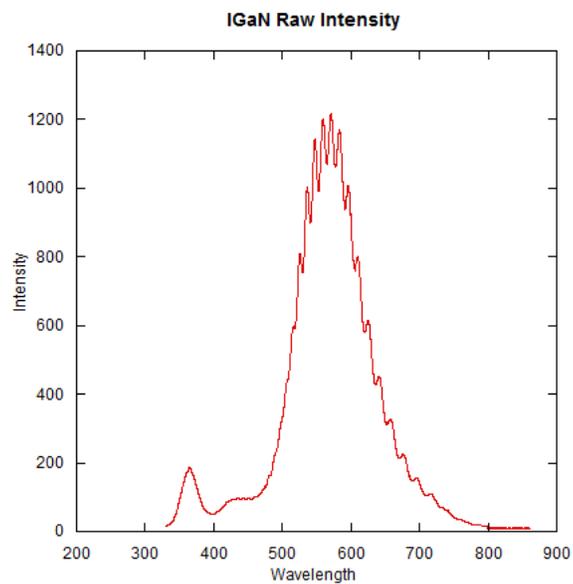


Figure 9: Intrinsic GaN Raw Intensity vs Wavelength

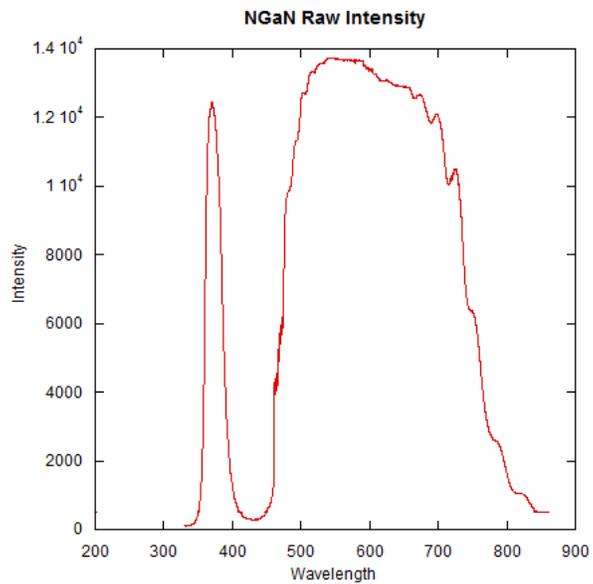


Figure 10: N-type GaN Raw Intensity vs Wavelength

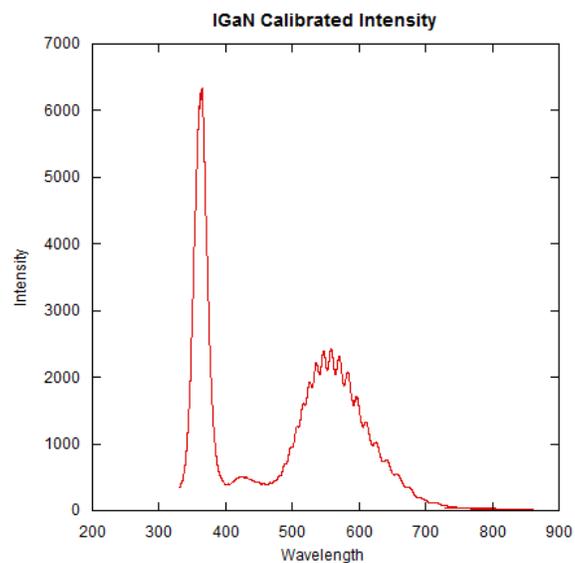


Figure 11: Intrinsic GaN Calibrated Intensity vs Wavelength

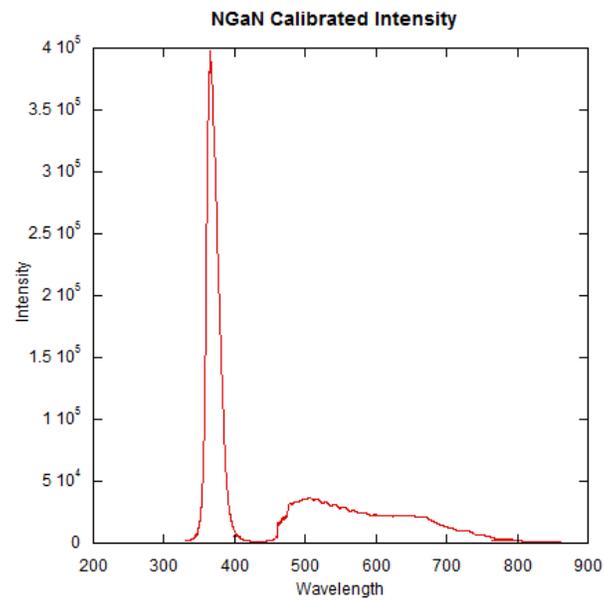


Figure 12: N-type GaN Calibrated Intensity vs Wavelength

5 Conclusion

Gallium nitride is one of the most important emerging semiconductor materials. Its unique physical and chemical properties make it suitable for a wide range of applications. The implementation of GaN devices will significantly impact our society by reducing production costs and increasing efficiency. One application of GaN, which is already being implemented, is in solid-state lighting. GaN-related materials also appear to be a better alternative to Silicon for the production of transistors with high efficiencies and might entirely replace the use of Silicon in such devices in the future.

Photoluminescence spectroscopy can be used to detect defects and impurities in GaN materials. We designed and built a system for taking photoluminescence measurements on GaN samples provided by Lightwave Photonics Inc. Our system uses a UV LED with nominal wavelength of 300 nm as a light source, instead of an expensive UV laser, which is typically used in photoluminescence spectroscopy. The measurements we took show the expected emission peak at 360 nm, as well as some defect-related luminescence in the yellow range. Considering the low-cost production method Lightwave Photonics used to make these samples, the luminescence we detected indicate satisfactory quality of their materials. The results we obtained suggest that it is possible to perform measurements on GaN materials using a UV LED light source.

6 Bibliography

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