Physical Characterization of Aluminum-Nitride Samples Using Photo-Luminescence Spectroscopy

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1 Abstract

This study aims to characterize the photoluminescent properties of aluminum nitride (AlN) samples, a material of great interest for next-generation semiconductor devices due to its ultra-wide bandgap of 6.2 eV. Using a 193 nm laser, photoluminescence (PL) spectra were obtained from AlN thin films and bulk samples. The collected data was analyzed by converting the wavelength of emitted light into photon energy, allowing for a detailed examination of the energy distribution. The PL spectra were further analyzed using the Lasher-Stern-Wurfel (LSW) model to extract key physical parameters. The findings reveal that the polarity of AlN has minimal impact on the luminescence peak, and the model provides valuable insights into the electronic properties of the material. These results contribute to the understanding of AlN's potential for high-power and deep ultraviolet (DUV) optoelectronic applications.

2 Introduction

2.1 Background

Aluminum Nitride (AlN) is an Ultra-Wide Bandgap Semiconductor that has gained significant interest in recent years for next generation semiconductor devices. AlN has a direct bandgap of 6.2 eV, far greater than that of a typical wide bandgap semiconductor such as Gallium Nitride (3.4 eV). This wide bandgap enables AlN to operate effectively in high-temperature and high-power environments, making it a promising material for advanced optoelectronic and electronic devices.

One of the primary drivers of research into aluminum nitride is its potential for use in deep ultraviolet (DUV) light-emitting diodes (LEDs), laser diodes, and high-frequency power electronics. Its high breakdown voltage and ability to handle large electric fields without deteriorating make it suitable for use in high-power devices. With recent developments in polarization induced doping of AlN, electrically driven AlN devices such as DUV laser diodes seem feasible to be fabricated in the near future.

2.2 Objective

The objective of this work is to characterize AlN structures using their photoluminescence (PL) spectra. Data will be fitted to the Lasher-Stern-Wurfel Model using non-linear least squares curve fitting. This model will then allow for the extraction of physical parameters regarding the samples.

3 Experimental Methods

A 193 nm laser beam was generated using an Excistar 500 tabletop laser system and directed onto 10 mm x 10 mm samples of aluminum nitride (AlN) via a 1 OD rectangular focusing lens. The sample was mounted vertically by adhering it to a copper extrusion with adhesive tape. Data was collected within a cryogenic probe station. Although all data was collected at room temperature, this allowed for consistent conditions should cryogenic data be of interest in the future.

The emitted light from the AlN sample was collected from its bottom edge and subsequently guided by a series of mirrors into a photo-spectrometer. The photo-spectrometer recorded the intensity of the light across a spectrum of wavelengths.

The resulting data was presented as a power distribution over a range of wavelengths. To analyze the energy distribution of the emitted photons, the recorded wavelengths were converted to photon energies using the equation

$$E = 1240/\lambda \tag{1}$$

where E represents the energy in electron volts (eV) and λ is the wavelength in nanometers (nm). This conversion allowed for the generation of an energy spectrum, indicating the intensity of emitted light as a function of photon energy, which formed the basis for the analysis of the AlN samples.

4 Results

After initial training data was collected to gain familiarity with the setup and procedure. The first experimented that was conducted was in attempt to differentiate the photoluminescent characteristics of Nitrogen-Polar and Aluminum-Polar samples of thin film Aluminum Nitrides grown via Molecular Beam Epitaxy (MBE) on bulk Aluminum Nitride Substrate.

Figure 1 shows the PL spectras of Al-polar and N-polar AlN thin films overlaid on each other. This data supports earlier findings from the Jena-Xing group using Cathode-Luminescence showing that the polarity of high quality MBE grown AlN has little to no impact on the wavelength of the luminescence peak. This is an important result as although it is more difficult to create N-polar crystal with a smooth crystalline surface, N-polar AlN is desirable for many devices as

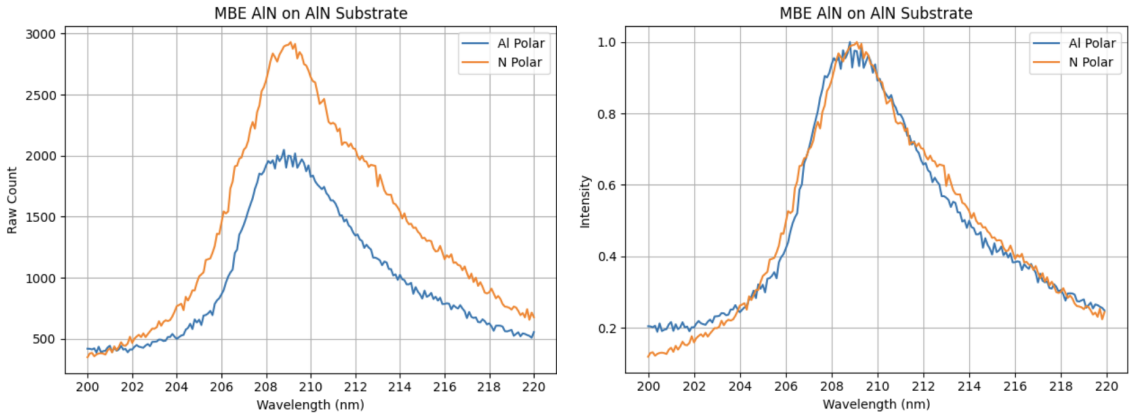

Figure 1: Photoluminescence spectra of Al-polar and N-polar AlN thin films

PL spectra data was also collected on bulk AlN substrate. The 10x10mm sample was cleaved using wafer cleaving pliers to leave a perfectly smooth crystalline side out of which data would be collected. This is also important as much of the context of this research was in regards to DUV laser diodes, which require 2 cleaved edges to act as a Fabry–Pérot resonator.

Figure 2 shows the relative intensity spectra of the cleaved AlN bulk sample. The peak to noise difference of roughly 3x is not as defined of a peak as seen in the MBE grown thin film, but is still sharp enough and at the expected location for relevant data to be extracted.

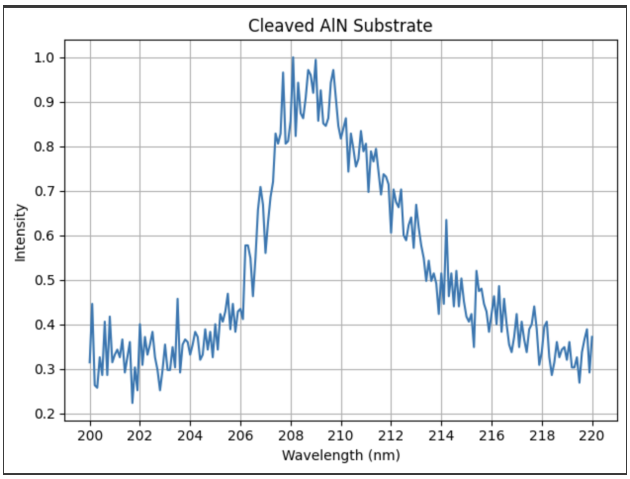

Figure 2: PL Spectra of Cleaved AlN Bulk Substrate

The Lasher-Stern-Wurfel Model is a way to model the emission spectra for a material. It utilizes an Arrhenius black-body component and a material specific absorptivity. The model is given by *Equation* 2.

$$I_{PL} = \frac{2\pi}{h^3c^2} * \frac{E^2 a(E)}{\exp\frac{E-\Delta u}{kT} - 1} \tag{2}$$

Where I is the intensity of the PL spectra as a function of the emitted light energy, E, h is planck's constant, c is the speed of light, Δu is the quasi-fermi level separation, k is boltzmann's constant, and T is the electron temperature in the material. The absorptivity $a(E)$ is calculated in *Equation* 3:

$$a(E) = 1 - \exp\left\{[\alpha(E, Eg, C) * T(E, \gamma)](f_v - f_c)(E, \Delta u, T)\right\} \tag{3}$$

The absorptivity is given in relation to the absorption coefficient, α, which is assumed to be proportional to the joint density of states, given by the square root of the difference between the energy and the bandgap. This absorption coefficient is then convolved with a peak function, T, to generate an Urbach tail. Finally, a correcting factor is taken into account regarding the partial filling of the valence and conduction bands. The model contains 4 parameters that can be fitted to. These parameters are the electron temperature, quasi-fermi level separation, Urbach tail width, and a general fitting parameter. Using SciPy's curve fitting package in python, we will attempt to extract these physical parameters from the measured data. To compensate for the underwhelming peak to noise ratio in the spectra, a uniform background noise of about 30% the peak, this corresponds to roughly the same base level as seen in the measured spectra.

The SciPy curve fitting package utilizes a non-linear least squares approach to find the best solution within certain parameter ranges. The initial guess of these parameters was set to typical values expected in bulk semiconductor crystals, and then reasonable ranges in which these values could be expected to be found were also set. Figure 3 shows the result of this curve fitting.

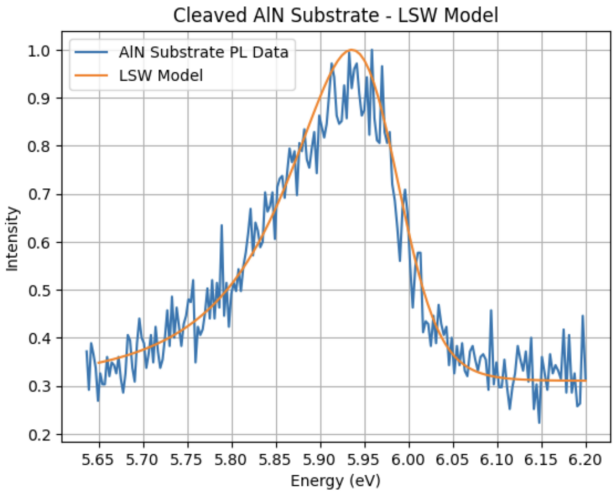

Figure 3: LSW Model Fitting on Cleaved AlN Substrate

The Model fits the data extremely well, and from it we are able to extract our desired physical characteristics. Our fitting claims that the electron temperature within the crystal lattice is $\sim$493K, the quasi fermi level separation is 5.922eV, and the width of the Urbach Tail is 0.150eV. All of these values are reasonably close to those expected based on photoluminescence studies of other semiconductors such as SiGe.

5 Discussion

This study focused on the photoluminescent properties of aluminum nitride (AlN) and examined how the material's polarity might influence its emission characteristics. The experimental results demonstrated that the polarity of AlN, whether Nitrogen-polar or Aluminum-polar, has negligible impact on the wavelength of its luminescence peak. This finding is consistent with prior research and confirms that we are able to fabricate both polarities of AlN with low enough defect rates such that they are viable for high-power and deep ultraviolet (DUV) applications.

The Lasher-Stern-Wurfel (LSW) model was employed to analyze the photoluminescence spectra, enabling the extraction of key physical parameters such as electron temperature and quasi-Fermi level separation. The model fit the experimental data well, validating the experimental approach and providing a deeper understanding of the material's electronic properties. Future work could involve conducting temperature-dependent photoluminescence measurements to investigate how the emission characteristics change under different thermal conditions. Additionally, exploring the influence of crystal defects on the photoluminescence could provide further insights into optimizing AlN for specific semiconductor applications.

6 Conclusion

This study successfully characterized the photoluminescent properties of AlN, demonstrating that the material's polarity has little impact on its emission spectrum. The application of the LSW model allowed for the extraction of important physical parameters, providing deeper insights into the electronic structure of AlN. These findings highlight the material's potential for use in advanced semiconductor devices, particularly in high-power and DUV optoelectronic applications. Future research should focus on temperature-dependent studies and further analysis of crystal quality have more context for the measured PL spectra.

7 References

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