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# LOW TEMPERATURE PHOTOLUMINESCENCE (PL) FROM HIGH ELECTRON MOBILITY TRANSISTORS (HEMTS)


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| **13. ABSTRACT** ***(Maximum 200 Words)***<br>The purpose of this report is to investigate the low temperature Photoluminescence (PL) from High Electron Mobility Transistor (HEMT) structures that have been modified by proton irradiation. The samples are aluminum gallium nitride (AlGaN)/gallium nitride (GaN) and indium aluminum nitride (InAlN)/GaN HEMT structures. These samples were cooled to 13 °K and excited with Continuous Wave (CW) lasers at 325 and 244 nanometers to look for PL originating from a Two-Dimensional Electron Gas (2DEG). | | | |
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## I. INTRODUCTION

As part of Defense Threat Reduction Agency (DTRA) funded work, the University of Alabama (UA) grew aluminum gallium nitride (AlGaN)/gallium nitride (GaN) and indium aluminum nitride (InAlN)/GaN High Electron Mobility Transistor (HEMT) samples and exposed the structures to various levels of proton irradiation. For electronics operating in extreme environments where the parts will be exposed to high energy radiation, performance degradation or failure is a major concern. GaN is a harder material and has a wider band gap than silicon, so making HEMT devices out of GaN should provide electronics that can perform better than silicon under extreme conditions. It is then necessary to understand how the HEMT structures are modified by high energy irradiation.

With HEMT structures, it is common to have Two-Dimensional Electron Gas (2DEG) which is confined at the interface between the semiconductor materials. The electrons at the interface can recombine in the GaN valence band, generating photons. This emission could be used to determine the effects of proton irradiation on a 2DEG. Exciting the HEMT samples directly at the interface at low temperatures should provide the best chance for detecting a 2DEG. To do this, the samples should be excited above the GaN band edge but below the absorption edge of the AlGaN or the InAlN.

## II. EXPERIMENTAL DETAILS

UA provided 10 HEMT samples and a GaN template sample. As shown in Figure 1 (provided by UA), five samples are InAlN/GaN and five are AlGaN/GaN. The HEMT structures used in this study were reference (unexposed) and proton irradiated at 2 mega electron volts of energy with a $10^{14}$ square centimeter flux.

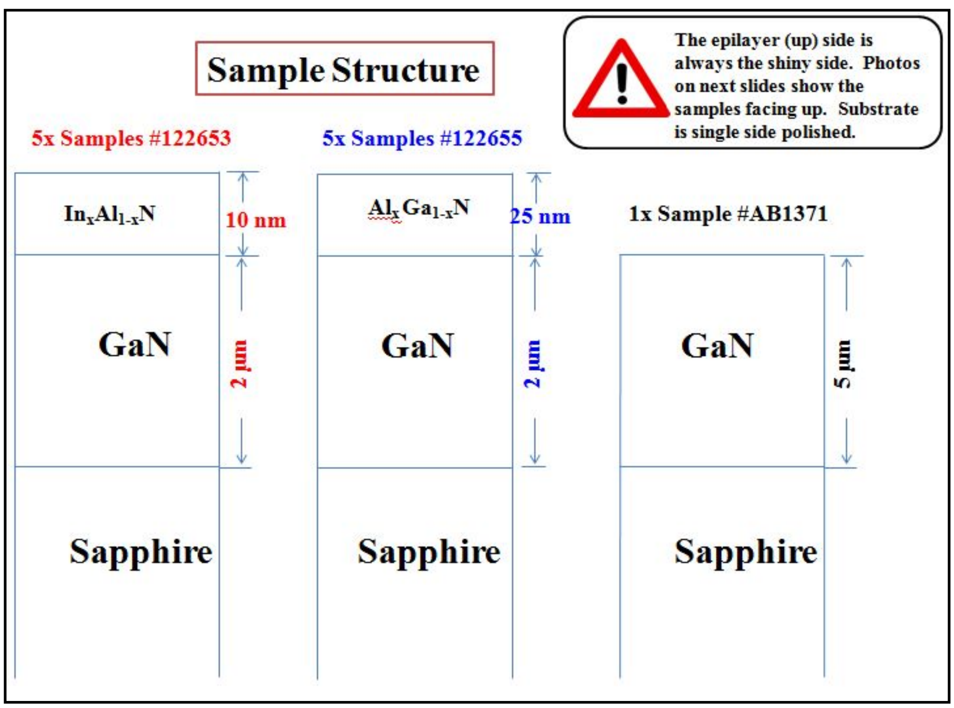


*Figure 1. HEMT Sample Structure*

For the measurements, the samples were loaded into a closed-cycle helium cryostat and cooled to 13 °K. Figure 2 shows the samples loaded into the cryostat. The samples were excited with two Continuous Wave (CW) laser sources. The first source was a 325-nanometer helium cadmium (HeCd) laser. The 325-nanometer light was collimated with a spot size of 1squared millimeter and a power of 0.95 milliwatts (95 milliwatts per square centimeter). The second source was collimated 244-nanometers light from a doubled argon ion laser also with a spot size of 1 square millimeter but with 3.8 milliwatts (380 milliwatts per square centimeter) of power. The Photoluminescence (PL) was collected with two 2-inch diameter off-axis parabolic mirrors and coupled into a 1mm core optical fiber. In front of the fiber, a long pass filter was used to eliminate the laser (Semrock filters for 325 nanometers and 266 nanometers). Figure 3 shows the experimental setup with blue lines to illustrate the excitation path and green lines to illustrate the collection path. The fiber coupled light was dispersed in a 30-centmeter single grating monochromator and detected by a liquid nitrogen cooled, back illuminated Charge Coupled Device (CCD) (Princeton Instruments Spec-10).

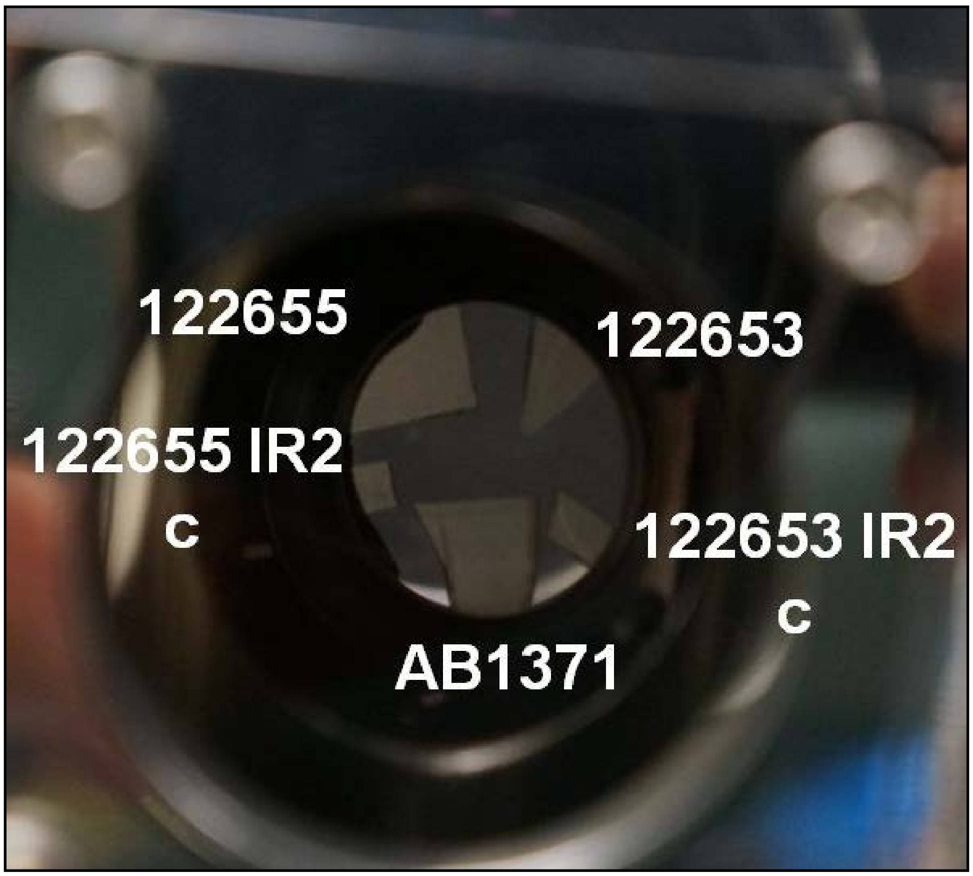


*Figure 2. HEMT Samples in Cryostat*

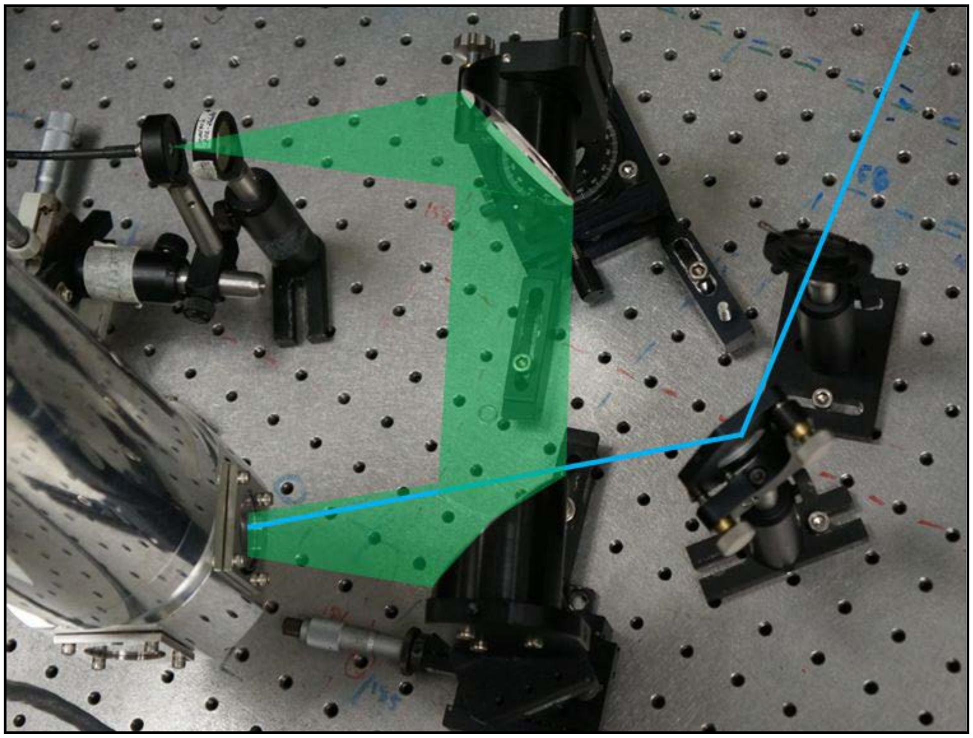

*Figure 3. Experimental Setup*

## III. EXPERIMENTAL RESULTS

The PL from the AlGaN/GaN samples, when excited at 244 nanometers, is shown in Figure 4. The GaN template sample exhibits a stong peak at 356 nanometers (3.48-electron volts). This corresponds to the bound exciton emission in the GaN. The same peak is present in both the reference and irradiated AlGaN/GaN samples, although at a lower rate due to absorption of the pump laser in the AlGaN layer. There is also a broad emission from 380 to 420 nanometers which is present in both the GaN template and AlGaN/GaN samples. There are two emission peaks in the AlGaN/GaN samples that are not in the GaN template. The first is at 306 nanometers (4.05-electron volts), and the second centered at 331 nanometers (3.75-electron volts). These samples have an aluminum concentration of 25 percent, which would correspond to a band gap near 4.09-electron volts [1,2]. For a band gap of 4.09-electron volts, emission at 4.05-electron volts would mean that the Stokes shift is negligible.

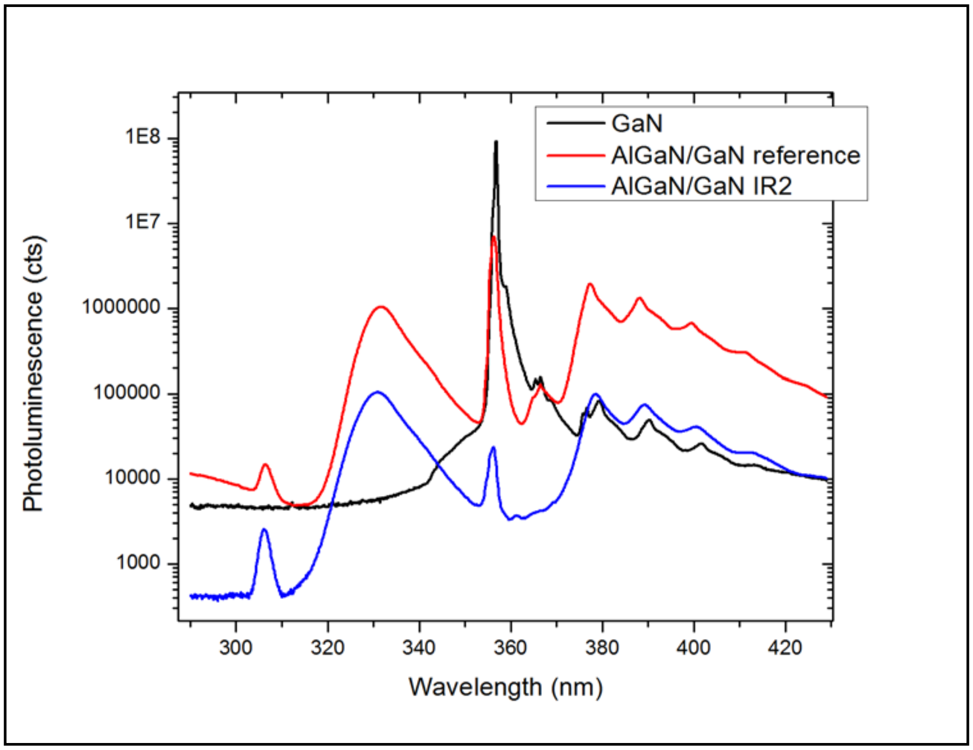


*Figure 4. 244-Nanometer Excitation PL at 13 °K From AlGaN Samples*

Room temperature PL was collected to determine which peak should be attributed to the AlGaN band edge emission. For the room temperature measurements, the samples were mounted in a sample holder outside of the cryostat to remove the effects that any impurities in the cryostat windows would play on the spectrum (the windows fluoresce under a 244-nanometer excitation). Figure 5 shows the room temperature PL from the GaN template and AlGaN/GaN reference samples at 300 and 13 °K. The bound exciton in the GaN shows a clear redshift of 56 milli-electron volts from 13 to 300 °K, consistent with thermal expansion in bulk semiconductors. However, of the two peaks that might be contributed to the AlGaN band edge, the 331-nanometer peak does not shift and the 306-nanometer peak blueshifts from 13 to 300 °K by 20 milli-electron volts. Neither behavior is typical for thermal expansion. In the room temperature measurements, the emission from 380 to 420 nanometers has vanished, indicating that it is typical behavior for a shallow defect state in the GaN. However, the 331-nanometer peak does not vanish, so while it could be a defect state in the AlGaN, the strength at room temperature and the lack of a temperature dependent energy shift points to anomalous behavior.

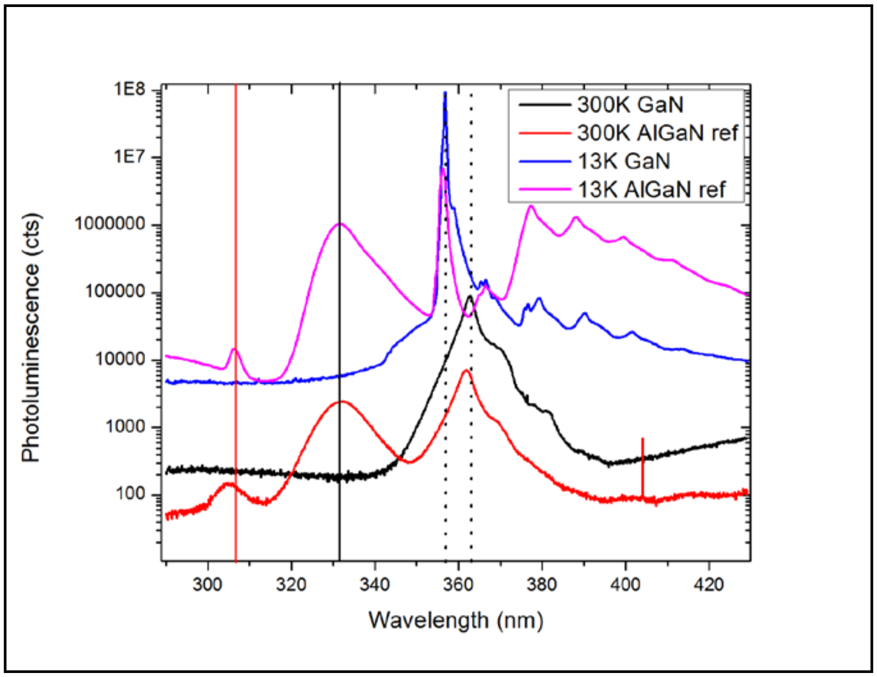


*Figure 5. 13 and 300 °K PL Measurements with 244-Nanometer Excitation*

Assuming that the AlGaN band edge is 4.09-electron volts, pumping at 325 nanometers should excite carriers in the GaN at the AlGaN/GaN interface. This would directly pump carriers into a 2DEG. As shown in Figure 6, the broad emission at 331 nanometers is still present. The spike and notch near 325 nanometers is due to the long pass filter and some leakage from the pump laser. Aside from the 331-nanometer emission which is still present, there is no additional emission that would provide an optical signature of a 2DEG.

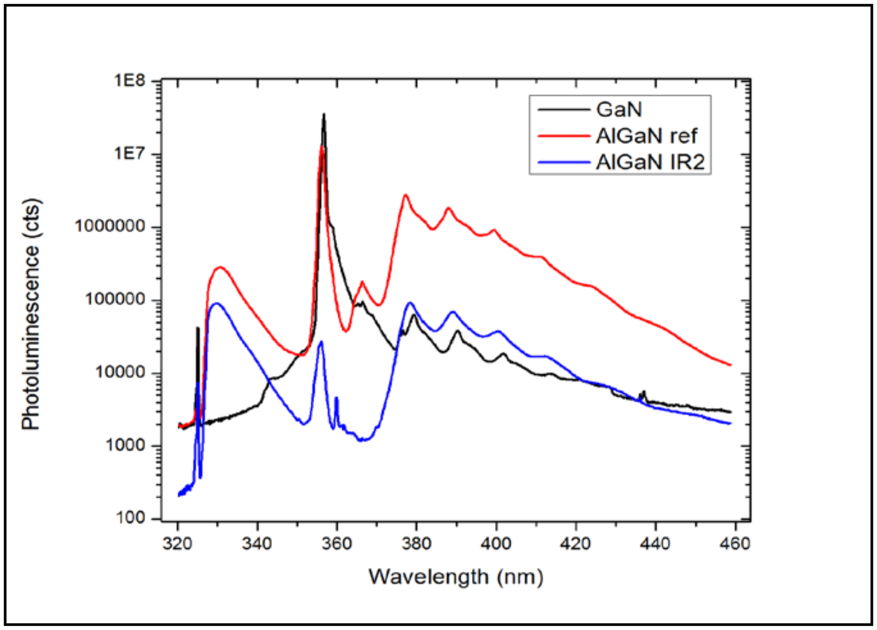


*Figure 6. PL at 13 °K From AlGaN Samples Excited at 325 Nanometers*

The PL at 13 °K from the 244-nanometer pump laser from the InAlN is shown in Figure 7. There are no new PL features in the InAlN samples that are not present in the GaN template. The indium concentration in the InAlN was 17 percent, which would create an absorption edge near 4.5-electron volts (276 nanometers) and an emission feature near 3.5-electron volts (354 nanometers) [3]. Pumping the InAlN at 244 nanometers would excite carriers into the InAlN.

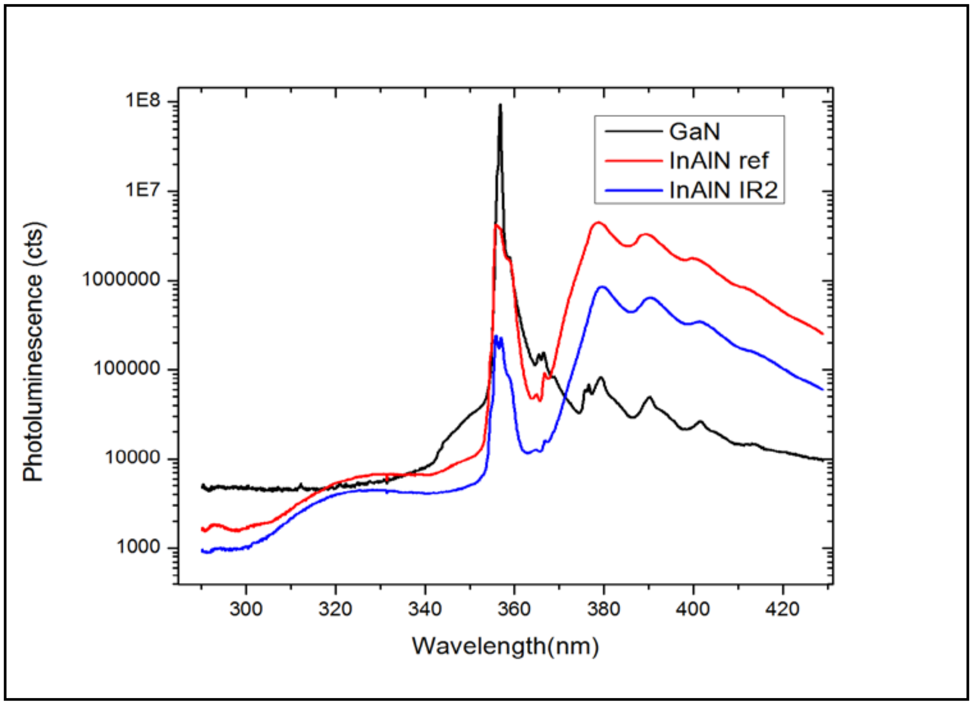


*Figure 7. 13 °K PL From InAlN Samples with 244-Nanometer Pump Laser*

The InAlN samples were also excited with the 325-nanometer laser to examine the emission from carriers created directly in the InAlN/GaN interface. This is shown in Figure 8. The 325-nanometer laser line can be seen, but there is no other emission that is different from the excitation at 244 nanometers. This shows no evidence of emission from a 2DEG.

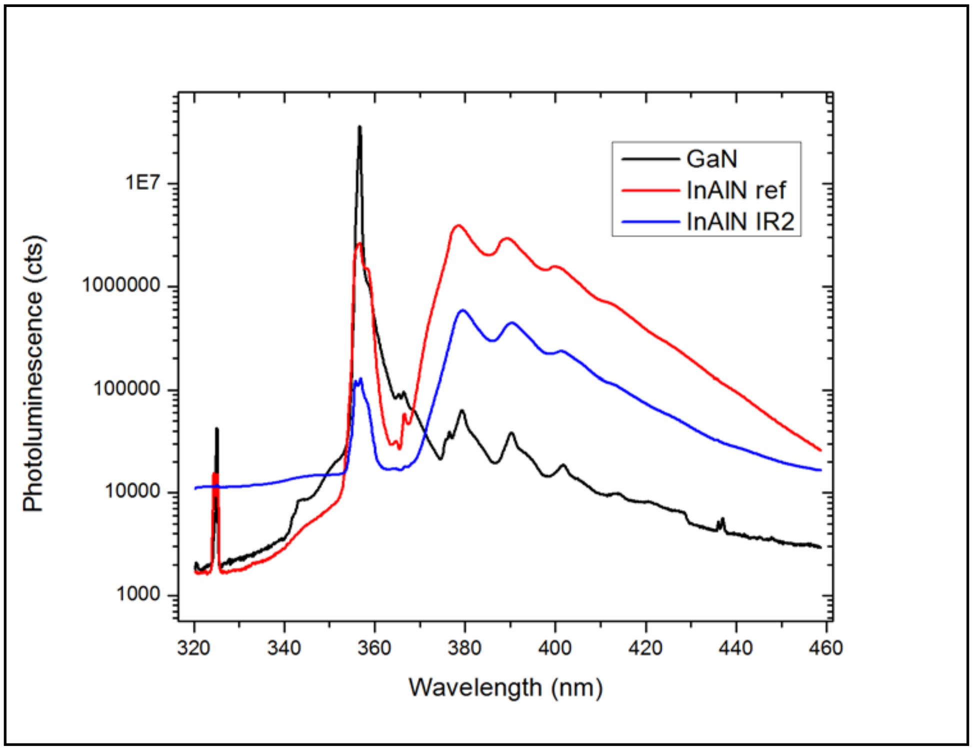


*Figure 8. 13 °K PL Emission From InAlN Samples Excited at 325 Nanometers*

## IV. CONCLUSIONS

The HEMT samples did not show any new emission features that would originate from the proton irradiation. The Irradiated (IR) samples (labeled IR2) showed weaker emission, which is consistent with a generation of non-radiative traps being generated during proton irradiation. With no new emission, electrical measurements will best characterize the irradiation damage. The intent of the United States (U.S.) Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC) measuring these samples was to test the emission at lower temperatures and at different energies than was currently available at UA. Neither the lower temperatures nor the different energies changed the nature of the emission detected from the HEMT samples. The only feature detected that was not present in measurements at UA was the 306-nanometer feature in the AlGaN feature which is of unknown origin. The additional measurements also point to the 331-nanometer emission being of different origin than AlGaN band edge recombination, which was originally hypothesized.

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## LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

| | |
|---|---|
| # | number |
| ° | degree |
| µm | micrometer |
| 2DEG | Two-Dimensional Electron Gas |
| AlGaN | aluminum gallium nitride |
| AMRDEC | Aviation and Missile Research, Development, and Engineering Center |
| CCD | Charge Coupled Device |
| cts | Counts |
| CW | Continuous Wave |
| DTRA | Defense Threat Reduction Agency |
| GaN | gallium nitride |
| He Cd | helium cadmium |
| HEMT | High Electron Mobility Transistor |
| InAlN | indium aluminum nitride |
| IR | Irradiated |
| K | Kelvin |
| nm | nanometer |
| PL | Photoluminescence |
| ref | Reference |
| U.S. | United States |
| UA | University of Alabama |
| X | times |

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