LEEN Characterization of Ohmic Contacts and Device Processing on AlGaN/GaN for HEMT Applications

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Abstract

Reliability and reproducibility of AlGaN/GaN semiconductors and metal contacts to the material are the limiting factors in producing GaN High Electron Mobility Transistors (HEMT's) on a commercial scale. While it is generally known which combinations of metals and ohmic contact processing produce low resistance ohmic contacts to n-type AlGaN/GaN, the mechanisms contributing to variations in the contacts and material quality are largely uncharacterized. Using Low Energy Electron-Excited Nanoluminescence (LEEN) Spectroscopy in an SEM, localized measurements of optical defect emissions were observed at the ohmic contact locations, which were also measured electrically with Transfer Length Method (TLM) measurements. A comparison of the yellow luminescence (YL) observed in the GaN with the TLM measurements provides a statistically significant correlation between deep level defects and ohmic contact performance. Several wafers with many die measured on each wafer indicate that sites with stronger YL produce contacts with higher resistance. Luminescence measurements have been used to detect regions producing HEMT's with uncharacteristically high sheet resistance for a given wafer. LEEN spectroscopy was also used to measure luminescence properties during device fabrication on unprocessed material, after ohmic contact annealing, and after gate metalization. The results show that changes can occur in the material even at low processing temperatures. For a material system that is intended for use as high frequency, high power applications, reliability at operating temperature can be affected. To verify that low temperature processing steps were occurring, unprocessed samples were annealed in air at 270 °C and analyzed with LEEN. The results show that material with the smallest change in luminescence properties achieve the most desirable ohmic contacts.

Project Objectives

As with all devices, AlGaN/GaN HEMT's are critically dependent on their contacts. Material quality and defects at the metal-semiconductor interfaces affect device contact quality. The defects found in the material and at interfaces are a strong function of growth and processing parameters. It is difficult to maintain uniform temperatures over the entire wafer when growing AlGaN/GaN device structures. This can result in variations in morphology, mole fraction, thickness, and material quality in general. It is equally difficult to control the properties of the metal-semiconductor interface under normal device processing procedures. The variations in processing and material preparation have drastic effects on repeatability and reliability of GaN devices. It is important to understand the role of each processing step used in the creation of these devices. It is the goal of this study to provide insight into the physical mechanisms behind the changes in device performance due to metal-semiconductor interface formation and material defects as well as the effects of device processing on the material.

Methodology Used

Samples used in this work were HEMT device layers grown on sapphire by MBE at AFRL at Wright Patterson Air Force Base. Samples A401, A418, A424, and A425 have the following structure: GaN (50 nm)/$Al_xGa_{1-x}N$ (67.5 nm)/UID-GaN buffer/SI-GaN (1 um)/AlN nucleation layer grown on a sapphire substrate. Each sample is a quarter of a 2-inch wafer and contains about 15 die. A401 and A418 have nominal mole fractions of $x = 0.15$, and A424 and A425 have nominal mole fractions of $x = 0.10$. All samples have a buffer thickness of 500 nm except for A418, which has a 250 nm thick buffer. Ohmic contacts were formed by annealing Ti(10 nm)/Al(100 nm)/Ni(50 nm)/Au(20 nm) at 800 °C for 30 s in a nitrogen ambient. All of the wafers were processed at the same time to eliminate any possible deviations related to the contact preparation.

At various stages in the device processing, the wafers were analyzed by LEEN [1] Spectroscopy in a JEOL 7800F SEM in Ultra-High Vacuum (UHV). LEEN Spectroscopy is a form of cathodoluminescence spectroscopy (CLS) [2] in which the incident electron-beam energy is varied to probe the sample as a function of depth. CLS is the spectroscopy of light emitted from a material when irradiated with electrons. Electrons with sufficient energy excite other electrons inside the semiconductor of interest from the conduction band to the valence band. These excited electrons are free to recombine with holes radiatively and nonradiatively. In order for the electrons to make radiative transitions from the higher energy level of the conduction band into states of lower energy, photons with energy equal to the difference in the energy levels of the states are emitted. LEEN Spectroscopy is employed as a tool for analyzing these radiative defect transitions caused by known and unknown defects in the material and at interfaces. Using this tool in an SEM, the defect properties of the HEMT layers can be observed at the location of the device under testing. This analysis can be performed over the surface of the sample and as a function of depth by varying the electron-beam energy. Beam energies used in these experiments range from 1.0 – 4.0 keV, which corresponds to penetration depths of 17 – 130 nm respectively. The depth dependent analytical capabilities of LEEN allow the discrimination between defect states found at the surface of the material and those found in the bulk layers. Using the SEM, LEEN spectra were taken in the middle of the largest contact spacing of the TLM structure on many die of each quartered wafer.

Optical emissions were collected in the 1.75 – 4.25 eV photon energy range. All emissions were normalized to the GaN bandedge emission. In order to reduce or eliminate time dependence in the spectra, the beam currents and energies were adjusted to low power levels. For all normalized spectra, the yellow luminescence signal was integrated from 1.75 – 2.70 eV. This integrated value, as well as other deep level emissions, was compared with contact resistance and sheet resistance values from die to die at different beam energies. Optical spectra were also compared as a function of device processing on a given device. Changes in deep level defect emissions were observed at different processing stages.

Electrical characterization of ohmic contacts formed on these samples consisted of TLM measurements [3] that provided values for specific contact resistance (ρ_c) and sheet resistance (ρ_s). TLM measurements are performed by plotting the resistance between contact pads of various spacing connected by the active layer of the device as a function of contact spacing. The slope of this plot yields sheet resistance and the y-intercept yields the contact resistance.

Results Obtained

Figure 1 shows a comparison of LEEN spectra as a function of processing on A401 die (6,11). There are four main features observed. AlGaN near bandedge emission (NBE) at 3.75 eV and GaN NBE at 3.45 eV are expected. There is also a large yellow luminescence (YL) contribution centered around 2.20 eV and deep level emissions found around 3.10 eV. Unprocessed material shows large YL and deep level emissions. After the ohmic contact anneal at 800 °C for 30 s, the YL and deep level emissions at 3.10 eV reduce dramatically. After gate metalization and lift off, the sample experiences a 270 °C anneal for 5 min to cure photoresist. The YL and deep level emissions at 3.10 again decrease. On this particular die, the defects are found to have higher luminescence intensity at higher beam voltages indicating that they are not at the immediate surface of the sample.

In order to verify that the low temperature gate processing was indeed having an effect on the luminescence spectra, unprocessed pieces of each sample were annealed in air at 270 °C for 5 min. Figure 2 shows this result. LEEN spectra show an increase in the deep level luminescence intensity after annealing in air at 3.10 eV. Furthermore, the samples with the largest increase in deep level emission intensity have the poorest contact resistance. A401 had an average contact resistance of 6.4×10^{-5} Ω-cm^2 while A418 had an average of 5.0×10^{-6} Ω-cm^2 over all die measured.

After all processing was complete, the integral of the YL was plotted as a function of contact resistance. Figure 3 shows this result. Samples with the highest YL intensity had the poorest contacts. The large number of data points makes a good statistical correlation even though there are many factors that can influence the data. Figure 4 compares the sheet resistance of the HEMT active layer with the AlGaN NBE energy level.

As expected, the samples with the highest NBE energy level have the highest Al mole fraction and hence the lowest sheet resistance. However, note that A418 has an outlier that is approximately 100% higher than expected. Upon further inspection, this particular die is shown to have midgap defects or a smearing of the AlGaN bandedge emission. Figure 5 shows a comparison between die (5,10), which is bad, and die (7,7), which is representative of all other die on A418. The uncharacteristic emission is prominent between the AlGaN and GaN bandedge emissions for die (5,10).

Significance and Interpretation of Results

The YL is associated with transitions from a shallow donor, e.g., a N vacancy, to a deep acceptor level, e.g., a Ga vacancy [4-8]. YL is often correlated with material quality. In this case, the presence of YL may serve to pin the Fermi level of the GaN at the ohmic contact to some value in midgap causing a higher than optimal contact resistance.

The deep level emission at 3.10 eV is believed to be from a deep acceptor. Mg is known to produce deep levels at around 3.25 eV in GaN and at higher concentrations of Mg the level can shift deeper into the bandgap [9]. It is possible that there is residual Mg contamination from the chamber as it was used for compensation doping in the buffer layer to achieve a semi-insulating layer. The fact that this peak reduces when annealed in nitrogen at high temperatures or with a photoresist cap on at low temperatures indicates that some type of water complex may play a role in activating or passivating these defect sites. This idea is supported by the experimental data in Figure 2 where annealing the samples exposed to atmosphere are subjected to water vapor. These deep level emissions indicate that Fermi level pinning may also play a role as well as some compensation effects that could reduce the effective doping of the device if they are from Mg impurities.

Using LEEN Spectroscopy, the HEMT structures have been characterized at the device location in a non-destructive fashion. The effects of processing have been observed. The role of defects in device performance can be understood because they can be studied at the contact area using LEEN in an SEM. These results show that material can be inspected spectroscopically to potentially predict what sort of device performance might be expected on a given wafer and at given sites on a wafer. The next phase of this project will involve the characterization of Schottky gate contacts to HEMT's in the same fashion while studying in-situ modification of the gate-semiconductor interface in UHV to make completed devices.

Figures and Charts

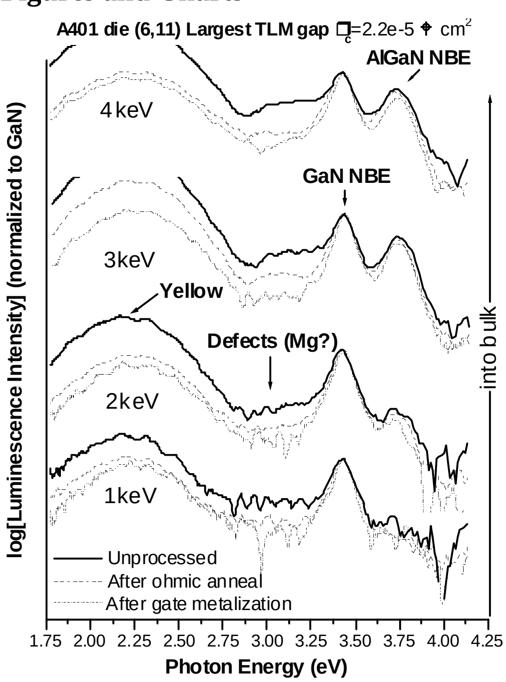

Figure 1. LEEN spectra of HEMT layer after various processing steps

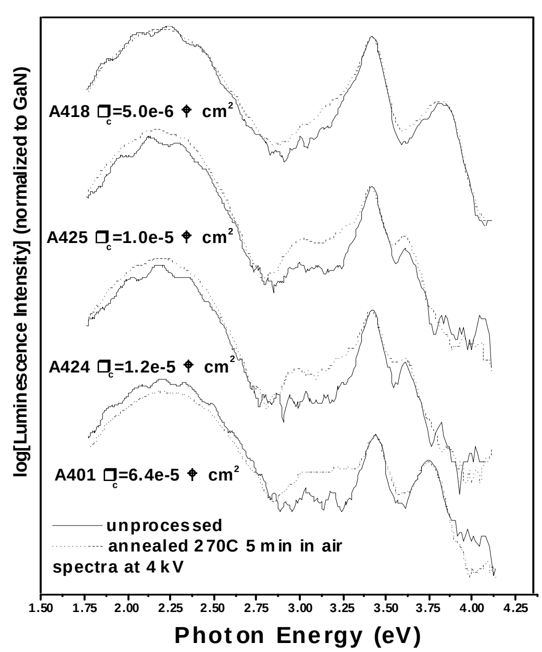

Figure 2. LEEN spectra at 4.0 kV of samples showing effect of air anneal on defect luminescence at 3.10 eV.

Figures and Charts (Cont.)

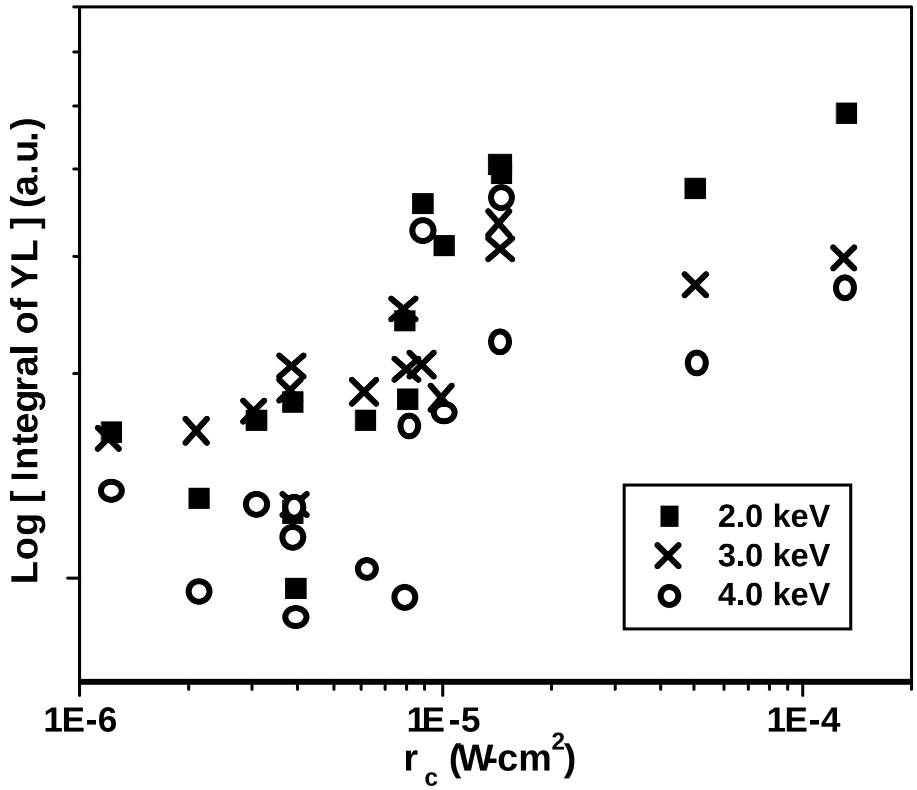

Figure 3. Integral of yellow luminescence as a function of contact resistance. There is a significant statistical correlation between the defect emission and increasing contact resistance. The trend is strongest at 2.0 and 3.0 keV

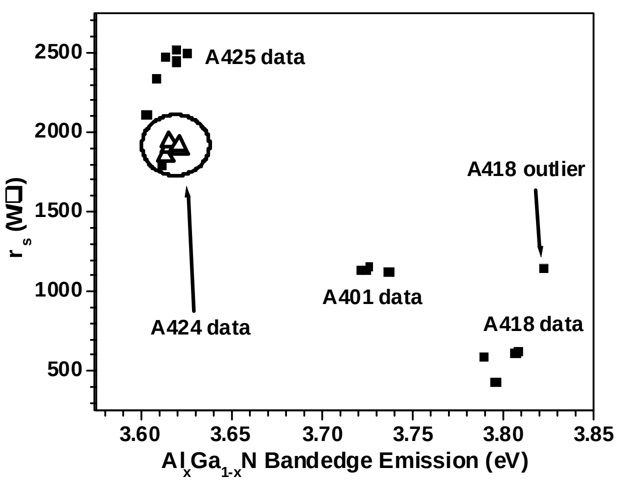

Figure 4. Sheet resistance compared to AlGaN NBE. Note the uncharacteristically high sheet resistance on the outlier on A418

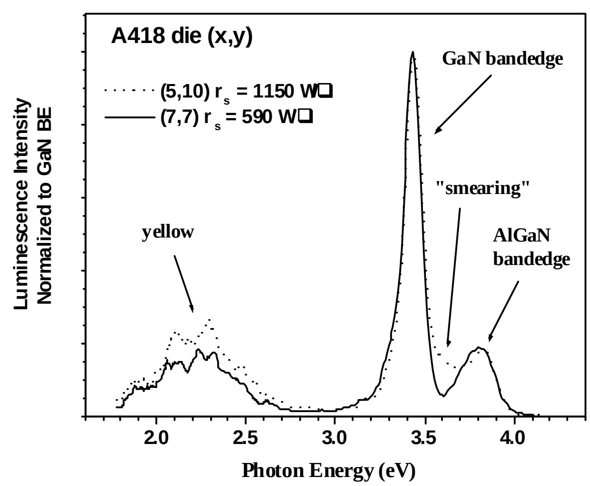

Figure 5. Spectra showing difference between good and bad sheet resistance on A418. On the die with high sheet resistance the AlGaN NBE is smeared

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