6.1 Summary and Conclusions

This section is intended as a summary of the research results obtained for the formation of metal-GaN interfaces on the GaN surface. The main objective of this research involves two main reasons: 1. Development of simple and inexpensive deep level transient spectroscopy system and 2. Fabrication and Characterization of Au and Pd Schottky diodes and study of deep levels in the n-GaN using deep level transient spectroscopy.

This thesis illustrates the several problems associated with GaN, an emerging technologically important material for applications in the field of short wave length optoelectronics and high-power/high-temperature electronics. It presents some technologically important and useful results towards the problems chosen for the investigation. The material properties and their importance and application of several opto-electronic/electronic devices of group III-nitrides such AlN, GaN, InN and their alloys have been reviewed in detail. The issues associated with metal GaN contacts, with still have to be solved have also been presented. The importance of the deep level studies in the present work has been reviewed. A sensitive and inexpensive DLTS system has been designed and built for the measurements of capacitance transients with the aim of determining the trap parameters in semiconductor devices. The system enables to acquire the DLTS spectra with several rate windows in a single temperature scan. The rate-windows automatically changes to over more than three decades for determination of activation energies. This system is reliable, flexible and easy in handling data acquisition and applied to study the deep levels in the n-GaN materials.

Fabrication of Schottky contacts has been made on n-GaN using Au and Pd rectifying metal. These Schottky diodes were annealed in a rapid thermal annealing system at temperatures, 300 °C, 400 °C and 500 °C for 1 min in nitrogen ambient. We have investigated the annealing temperature effects on Schottky Barrier heights and structural properties of Au/n-GaN, Pd/n-GaN by current-voltage (I-V), capacitance-voltage (C-V), and X-diffraction (XRD) measurements. Also depth profile studies for
Au/n-GaN and pd/n-GaN have been made using Rutherford backscattering spectrometry (RBS) and Auger electron spectroscopy (AES) measurements respectively.

The barrier height of the as-deposited Au/n-GaN Schottky diode is found to be 0.85 eV (I-V) and 1.40 eV (C-V) respectively. However, the Schottky barrier height of the diode slightly decreased to 0.77 eV (I-V) and 1.24 eV (C-V) when the contact is annealed at 300 °C for 1 min in a nitrogen atmosphere. After annealing at 400 °C, the Schottky barrier height is slightly increased to 0.83 eV (I-V) and to 1.30 eV (C-V). Upon increasing the annealing temperature up to 500 °C, the barrier height decreased to minimum values of 0.73 eV (I-V) and 1.02 eV (C-V). The RBS and XRD results showed the inter-diffusion of the Au and Ga, leads to the formation of Au-gallide interfacial phases such as GaAu2, Au0.87Ga0.13 at the metal/GaN interface after annealing temperature at 300 °C and 400 °C. This may be the reason for the variation in the barrier heights when annealed at different temperatures.

The barrier height of the as-deposited Pd/n-GaN Schottky diode was found to be 0.80 eV (I-V) and 1.32 eV (C-V) respectively. However, the Schottky barrier height is slightly increased to 0.87 eV (I-V) and 1.44 eV (C-V) when the contact is annealed at 300 °C for 1 min in a nitrogen atmosphere. After annealing at 400 °C, the Schottky barrier height is slightly decreased to 0.79 eV (I-V) and 1.42 eV (C-V). Upon increasing the annealing temperature up to 500 °C, the barrier height still decreased to 0.73 eV (I-V) and 1.33 eV (C-V). The AES and XRD results showed that the Ga2Pd and Ga3Pd3 interfacial phases are formed at the metal/GaN interface upon annealing temperature at 300 °C. This may be the reason for the increase in the barrier height and a corresponding reduction in the reverse leakage current.

Later, we have investigated the deep level studies on Au/n-GaN as deposited and 400 °C annealed Schottky diode. The deep level parameters are determined with the help of home-built DLTS instrument. Three defect levels (A, B, C) were detected in as-deposited Schottky contact. The thermal activation energies of the traps “A”, “B” and “C” are estimated to have an activation energy level at Ec - 0.56 eV, Ec - 0.29 eV and Ec - 0.21 eV at temperatures 330 K, 225 K, 145 K respectively. The electron capture cross-section (σn) of the “A” defect is estimated to be 1.4 x 10^-18 cm². The trap concentrations (N_T) for the defect levels A, B, and C are determined. The values are 2.072 x 10¹⁸ cm⁻³, 4.144 x 10¹⁶ cm⁻³, 6.211 x 10¹³ cm⁻³ respectively. But in

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the case of the 400 °C annealed sample only two deep levels were detected \((A, B)\). It has been observed that the defect concentration gets reduced on annealing the Au/n-GaN Schottky diode at 400 °C temperature. Future DLTS investigations will include determination of whether the defects are acceptor-like or donor-like in their interactions with free carriers.

6.2 Recommended future research

The work presented in this thesis should be considered the beginning of the investigation of metal-GaN interfaces. There are issues that are unresolved and some that were not covered. More research regarding the formation of metal-GaN interfaces is required. Future research work involving metal-GaN interfaces and cleaning of nitride based semiconductors, fabrication of HEMT, MESFET and high voltage diodes using Schottky contacts on atomically clean material should be investigated. Also, the interface between clean GaN and insulating materials such as SiO\(_2\) and Si\(_3\)N\(_4\) should be investigated to determine the valence band offsets for potential application in MISFET devices. From the results of the experiments undertaken in this thesis further research should involve the further investigation of temperature effects of the Schottky barrier height of metal-GaN contacts. The metallurgical, structural and electrical properties of annealed interfaces must be investigated for future high temperature device applications. The nature of reactions between the metal and GaN should be further investigated, via TEM, SIMS, XPS, and Photoemission. Investigation regarding the determination of a contact scheme that will not react with the GaN substrate at elevated temperatures should be undertaken. Contact materials such as metal silicides should be investigated.

The investigations regarding metal contacts to GaN were restricted to n-type material. However, future application of GaN will require obtaining well behaved rectifying as well ohmic contacts for both n-and p-type material. It is important to determine the effect dislocation densities on the electrical properties of Schottky contacts. How the parameters such as the barrier height, ideality factor, leakage currents and breakdown voltage affected by achieving low dislocation densities in clean material?

Not only has considerable progress been made in metal-contacts field over the last few years, but further advances in understanding and control over defects were clearly indicated. The observation of annealing effects of electron traps in GaN and
the discovery of the conditions for which they are well-resolved provides impetus for future DLTS characterization of these traps under different experimental conditions. DLTS is a sensitive technique to detect and characterize deep levels in the space charge region of Schottky or pn-junction diodes, but is of limited use in wide band-gap semiconductors, since it relies on thermal ionization of deep levels. Therefore, DLTS can only detect deep levels with activation energies, 1 eV for practical trap parameters and measurement conditions. The DLTS system could be extended to better characterize these traps is to incorporate optical excitation. ODLTS enables characterization of deep levels throughout the band gap of GaN by using monochromatic light for carrier excitation. Also an important development in this field, instrumentation has to produce experimental arrangements and to use signal processing to make analysis of the results more straightforward which is applicable to wide band gap materials and to more resistive samples.