# CHPATER 1

# INTRODUCTION

## 1.1 Research Background of the III-Nitrides Electronics

### (a) Materials properties of III-nitrides

III-Nitrides based semiconductor materials have been widely used in device applications for blue and ultraviolet (UV) wavelengths light emitting diodes [1]. Both wurtzite and zinc-blend structures are available if grown on proper substrates. As illustrated in Fig. 1-1, AlN, GaN and InN have direct room temperature bandgaps of 3.4, 6.2 and 1.9 *eV*, respectively at room temperature. The wide band gap nature makes them promising for high temperature applications, because they have less intrinsic carriers at much higher temperatures than materials like Ge, Si and GaAs. The other attractive property of III-V nitrides is that they have very high breakdown fields. The critical electric field for the breakdown scales roughly with the square of the energy band gap of the material, and is estimated to be >4 MV/cm for GaN [2], as compared to 0.2 and 0.4 MV/cm for Si and GaAs, respectively. Figure 1-2 is a plot of avalanche and punch through breakdown of GaN Schottky diodes calculated as a function of doping concentration and layer thickness. It can be seen that 20 kV may be obtained for devices with ~100 μm thick GaN layer at doping concentration $<10^{15}$ $cm^{-3}$.

GaN has also excellent electron transport properties, including good mobility, and high saturated drift velocity as shown in Fig. 1-3 [3], thus making this material suitable for high frequency device applications such as microwave rectifiers. The materials properties associated with high temperature, high power, and high frequency application of GaN and several conventional semiconductors are summarized in Table I. It is anticipated that GaN may eventually prove to be superior to SiC in these application.

### (b) AlGaN/GaN heterostucture for high electron mobility transistors

In the past several years, the field effect transistor (FET) structures have been widely used for device applications, because FETs demand less complexity material growth and device fabrication as the bipolar transistors. The rapid progress on the GaN based modulation-doped FETs (MODFETs) has shown that GaN and related alloys will play a significant role in the future development of high temperature, high power, and high frequency electronic devices.

Figure 4 is a schematic representation of an AlGaN/GaN heterostucture. Due to the large conduction band discontinuity, the electrons diffuse from the large bandgap AlGaN into the smaller bandgap GaN and form a two-dimensional electron gas (2DEG) in the triangle quantum well at the interface, which is the hallmark of MODFET. The sheet carrier density of the 2DEG was found to be further enhanced by the strong piezoelectronic effect in GaN. Piezoelectronic coefficients in nitrides were measured to be about an order of magnitude higher than in traditional Group III-V semiconductors [4]. Theoretical simulations have predicted a high peak electron velocity of ~3x$10^7$ cm/s [5] and an electron mobility of ~2000 $cm^2/V$ s in GaN channel at room temperature at a carrier concentration of $10^{17}$ $cm^{-3}$ [6]. Gaska *et. al.* measured the highest Hall mobility of GaN growth on 6H SiC at room temperature which was 2019 $cm^2/V$ s, and the value increased approximately fivefold to 10,250 $cm^2/V$ s when measured at 10 K.

In 1993, Khan et al. demonstrated the first AlGaN/GaN MODFET, with a $g_m$ of

23 ms/mm and 2DEG mobility of 563 cm$^2$/V s at 300 K. They also reported the first microwave results with relatively poor frequency response. This is consistent with the defect-laden nature of the early GaN and AlGaN layers. With improvements in the materials quality, the transconductance, current capacity, drain breakdown voltage in GaN HFET are increased to a point that GaN-based MODFETs are now strong contenders in the arena of high power devices/amplifiers. To date, the highest power density achieved for a 0.45 x 125 *μ*m GaN MODFET is 6.8 W/mm at 10 GHz with associated gain of 10.65 dB [7]. The operation temperature has been pushed to 750℃ by employing a thermally stable Pt/Au gate contact [8].

### (c) Dry etch technique and damaging effects for III-nitrides

In practical AlGaN/GaN HEMT fabrication, dry etching has been proven to be an effective technique for the formation of mesas. However, exposure to the energetic ions may result in significant material damages, which often degrades the materials properties and device performance. ICP technique uses lower ion energies than reactive ion etching (RIE), and thus in general has lower damage levels as a result. Plasma-induced damage to GaN may take several forms, all of which lead to the changes in its electrical and optical properties, as follow:

1. Ion-induced creations of lattice defects, generally behave as deep level states, and thus produced compensation, trapping or recombination in the material. Due to channeling of the low energy ions that strike the sample, and the rapid diffusion of the defects created, the defects as deep as 1000 Å were measured from the surface, even though the projected range of the ions is only $\leq$ 10 Å[9-10].
2. Unintentional passivation of dopants by atomic hydrogen. The hydrogen may be a specific component of the plasma chemistry, or may be unintentionally present

from residual water vapor in the chamber or for sources such as photoresist mask erosion. The effect of the hydrogen deactivation of the dopants is a strong function of substrate temperature, but may occur to depths of several thousand angstroms.

3. Creation of non-stoichiometric surfaces through preferential loss of one of the lattice elements. This can occur because of strong differences in the volatility of respective etch byproducts, leading to enrichment of the less volatile species, or by preferential sputtering of the lighter lattice element if there is a strong physical component to the etch mechanism. Typical depth of this non-stoichiometry are less than 100 Å.
4. Deposition of polymeric film from plasma chemistries involving $CH_x$ radicals, or from reaction of photoresist masks with $Cl_2$-based plasma.

To date, much less is known about the electrical effects of dry etch damages, and its subsequent removal by chemical treatment or annealing in the GaN system than in other compound semiconductors. Most past work in this area was focused on n-type materials. The sheet resistances of GaN, InGaN, AlInN and InN samples were found to increase in proportion to the ion flux and the ion energy in an ECR Ar plasma[11-12]. Ren *et. al.*[13] examined the effect of ECR $BCl_3/N_2$ and CH4/H2 the plasmas on the electrical performance InAlN and GaN channel field effect transistors. They found that hydrogen passivation of the Si doping in the channel may occur if $H_2$ is a part of plasma chemistry and that preferential loss of $N_2$ degraded the rectifying properties of the Schottky contacts deposited on plasma-exposed GaN surfaces.

There is no information available on the electrical effects of plasma damages on AlGaN materials. In the AlGaN/GaN HEMT fabrication, the Schottky contact is deposited on AlGaN to form the gate electrode, the capping layer (n type) for Ohmic contact should be removed, the process is called gate recessing. Due to the plasma damaging effect, the Schottky characteristics of the GaN diode will be degraded. A low power ICP etch process should be used in gate recessing to avoid the creation of interface states to improve the diode properties.

### (d) The Ohmic contact and Schottky contact materials for AlGaN/GaN HEMT

The Ohmic contact and Schottky contact are needed for source/drain and gate electrode, respectively. The ideal metal/semiconductor interface should be free of oxide and defect, uniform and thermally stable. Analysis by spectroscopic ellipsometry show that overlayer consisting of organic,inorganic, and native oxide with thickness larger than 30 Å is present on air-exposed GaN [14]. It was found that HCl-based solution is effective in removing oxides and leaves very few oxygen residues, however HF is more effective in removing carbon and hydrocarbon contamination[15].

The thermal stability of metal/GaN contacts is of critically important for practical device operation (especially for power electronics). The thermal stability limits of most of the metal/GaN contacts are between 300 and 600℃[16]. At higher temperatures, severe degradations in the contact morphology were observed, usually resulting from the formation of new interfacial phases, such as metal gallides. Ti/Al system has been widely used for Ohmic contact [17-18]. Ti reacts with GaN and forms TiN. A heavily doped *n* type is caused due to the creation of a high concentration of nitrogen vacancies [19]. Al serves as a good Ohmic contact after proper annealing. However, Ti and Al are easily prone to oxidation in the air. To prevent oxidation, Au is usually used to passivate the surface of the Ti/Al film. In general, nonuniform current flux and degraded microstructure were results of the formation of spiky interface and rough surface. Ni is therefore used as the diffusion barrier between Au and Al.

Schottky contact is very important in the HEMT fabrication for III-V compound semiconductor devices. In order to realize the materials for high temperature applications, high quality Schottky contact operating under high temperature without deteriorating the performance of the devices is required. The Schottky barrier heights of a variety of elemental metals including Ni, Au, Pt, and Pd on n-GaN have been investigated [20]. In addition, the thermally stable Schottky materials such as Ni, NiSi, Pt, PtSi, Pd, Re, PdIn, and Ni/Ga/Ni have also been reported [21-24]. $\beta$-$W_2N$ phase was found at W/GaN interface at annealing temperatures between 600 and 1000℃. It serves as a very good Ohmic contact due to the nitrogen vacancies creation by $\beta$-$W_2N$ formation. $TiWN_x/Ga_{0.51}In_{0.49}P$ contact with excellent thermal stability and electrical characteristics has also been demonstrated with barrier height and ideality factor of 1.00 eV and 1.04, respectively, after rapid thermal annealing (RTA) at 850℃ for 10 seconds[25]. However, the Schottky contact characteristics of the refractory transition metal nitrides such as titanium tungsten nitride ($TiWN_x$) and tungsten nitride ($WN_x$) with GaN have never been investigated.

## 1.2 Overview of the Dissertation

In this dissertation, AlGaN/GaN HEMT fabrication for high temperature applications is the main focus. Different structures of AlGaN/GaN HEMTs, including capped and uncapped AlGaN/GaN HEMTs, are studied in this research, and the growth of the structure were implemented by MOCVD. The device fabrication techniques were developed specially for high temperature applications including metallization, etch techniques. Finally, the DC and high frequency characteristics were measured and discussed. The III-nitrides epi-layers and related devices in our researches were all grown by metalorganic chemical vapor deposition (MOCVD) system.

In chapter 2, the Emcore made MOCVD system will be briefly described, including the in-situ monitoring technology. Most of the epitaxial films in this dissertation were grown by Emcore D-75. Next, the growth conditions for both GaN and $Al_xGa_{1-x}N$ on sapphire will be described. The materials characteristics and crystallographic qualities will be discussed. The materials were characterized by x-ray diffraction, Hall measurement and SEM (scanning electron microscopy). PL analysis will be emphasized in this chapter. The near-band-edge emission of the u-GaN at low temperatures will be investigated in details. Finally, we will discuss the 2DEG phenomena of the AlGaN/GaN heterostructures.

In chapter 3, PEC (photoenhanced chemical) wet etch and ICP (inductively coupling plasma) etch techniques were investigated. Parameter optimizations for both techniques were performed on different nitrides, including AlGaN, GaN and InGaN. Schottky diodes were used to characterize the surfaces after etching. The $n$ (ideality factor) and $\phi_b$ (barrier height) are very good index in evaluating the surface quality after etching. By extracting the $n$ and $\phi_b$, we could identify the quality of the etched surface and thus optimize the process parameters. The mechanisms were also proposed for both etching techniques.

In chapter 4, metallization was emphasized, especially the high temperature stability of the Ohmic and Schottky contacts. To develop high-temperature durable electronic devices, the thermal stabilities of Ohmic and Schottky contacts to GaN are essential. Tl/Al/Pt/Au and TiWN were chosen respectively as the Ohmic and the Schottky contact materials for this purpose. $WN_x$ was proved to be thermally stable at high temperatures. All of these facts were all verified by material analysis such as X-ray, SIMS (secondary ions mass spectroscopy), TEM (transmission electron microscope). The DC performances were also evaluated at high temperature in order to verify the high temperature applicability of the process developed.

In chapter 5, the full process of the GaN HEMT was described. In addition to the processes mentioned in the previous chapters, isolation and passivation were also performed since they were typical process techniques for device fabrication.. All of the techniques developed in the previous chapters were applied to the fabrication of the HEMTs. Both HEMTs with T-gates made by Ni/Au and $WN_x$ Schottky contacts were both demonstrated. Finally, DC performance at high temperatures for the HEMTs fabricated was discussed.

## 1.3 References in Chapter 1

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