A Technical Note on Gallium Nitride Technology and short Qualitative Review of its Novel Applications*

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Abstract
The increasing importance of the Gallium Nitride (GaN) Technology in finding newer applications in the device fabricatioin, has led to a spurt in the research efforts on this evolving topic. The present paper discusses technically (a) Designing based on the interdependence of the important performance parameters, (b)Some of the important devices like – (i) New Kind of Nanotubes, (ii) Laser Diodes, (iii) High-resolution Printings, (iv) Solar Cells, and (v) Microwave Radio-Frequency and Power Amplifiers, besides bringing out the salient features of GaN technology. The novel papers on the subject depicting the newer trends and novel applications have also been qualitatively reviewed.

Keywords: GaN Technology, GaN Devices.

Resumen
La creciente importancia de la tecnología del Nitrato de Galio (GaN) de encontrar nuevas aplicaciones en la fabricación de dispositivos, ha conducido a una aceleración en los esfuerzos de investigación sobre este tópico en desarrollo. El presente artículo discute algunos aspectos técnicos sobre: (a) El diseño basado en la interdependencia de parámetros de desempeño importantes, (b) Algunos dispositivos importantes tales como – (i) Nuevos tipos de Nanotubos, (ii) Diodos Laser, (iii) Impresoras de alta resolución, (iv) Celdas solares y (v) Amplificadores de potencia y de frecuencia de micro ondas de radio, todo esto muestra la importancia de la tecnología del GaN. Los artículos recientes sobre el tema muestran las nuevas tendencias y nuevas aplicaciones que han sido revisadas cualitativamente.

Palabras clave: Tecnología del GaN, Dispositivos de GaN.

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I. INTRODUCTION

It is now well established [1, 2, 3] that GaAs and GaN are very useful in the semiconductors, electronics and spintronics industries is Recently; Chopra [4, 5, 6, 7, 8, 9] has made important studies on the use of GaAs and GaMnAs in Spintronics, and Sensor and Deceiving Technologies. A lot of interest has been recently shown in Gallium Arsenide Technology and Devices based on this technology. However, because of various advantages of GaN over GaAs in the devices being made by GaAs technology, GaN is taking over as the more handy and suitable material for the fabrication of the semiconductor devices. It is being accepted as the next important semiconductor material. It has the advantage that it can be operated at high temperatures. Also, it has wide band gap energy. It has great potential, and is regarded as key material for the next generation of high frequency and high power transistors. GaN with a high crystalline quality can be made by depositing a buffer layer at low temperatures, and because of its high-quality has led to the fabrication of the p-type GaN, p-n junction blue/UV-LEDs, and and the room-temperature stimulated emission, which is required for the laser action, Because of the establishment of this utility, some commercial firms have developed (i) the high quality blue LEDs, (ii) violet-laser diodes with long life, and (iii) the nitride based devices like UV detectors and high speed field effect transistors (FETs). High brightness GaN LEDs have been developed for all the primary colors, which have applications in - daylight visible full color LED displays, white LEDs, and blue laser devices. Interestingly, the initial development of the GaN-based high-brightness LEDs was based on the thin film of GaN deposited by the MOCVD on sapphire.

At present, the Group III nitride semiconductors are recognized as the most promising semiconductor for making the optical devices in the visible short wavelength and UV region. GaN crystals are generally grown in the laboratory from a molten Na/Ga melt held under 100 atm pressure of N_2 at 750 °C. The problem encountered is that as Ga does not react with N_2 below 1000 °C, and hence the powder is made from something more reactive, by either of the following ways:

(i) $2Ga + 2\,NH_3 \rightarrow 2\,GaN + 3\,H_2$,

(ii) $Ga_2O_3 + 2\,NH_3 \rightarrow 2\,GaN + 3\,H_2O$.

However, commercially, the GaN crystals are grown using the technique of the molecular beam epitaxy (MBE). In certain cases, this technique is further modified to reduce dislocation densities, which is done by first applying an ion beam to the growth surface for creating the nanoscale roughness, and subsequently polishing the surface, by carrying the process in a vacuum.

GaN exists in two forms: (i) Hexagonal (Alpha) GaN, and (ii) Cubic (Beta) GaN. The properties of (Alpha) GaN are: is stable, has Wurzite Structure, has density 6.095 g/cm^3 at 300K, has lattice parameters at 300K as - a_0 = 0.3189 nm, c_0 = 0.5185 nm, has direct Energy Gap E_g, whose value at 293-1237 K = $3.556 - 9.9\times10^{-4}T^2 / (T+600)$ eV., has Energy Gap E_g at 300 K ~ 3.45eV, and has Energy Gap E_g at ca. 0 K = 3.50 eV. The parameters of Cubic (Beta) GaN are: is Meta-stable, has Zinc Blende Structure, has density 6.10 $g.cm^{-3}$ at 300K, and has lattice parameters at 300K as- 0.450 nm., has Energy Gap E_g at 300 K ~ 3.24eVm, and has Energy Gap E_g at ca. 0 K = 3.30 eV. Some other parameters of GaN in general are: Bandgap (eV) – 3.44 (Direct); Electron Mobility (cm^2/Vs) – 900, Hole Mobility (cm^2/Vs) – 10; Critical Field *EC* (V/cm) – 3000,000, Thermal Conductivity (W/mK) – 100 (200 Film); and coefficient of Thermal Expansion (ppm/K) – 5.4-7.2.The Bandgap of semiconductors is related to temperature (in Kevin K) by:

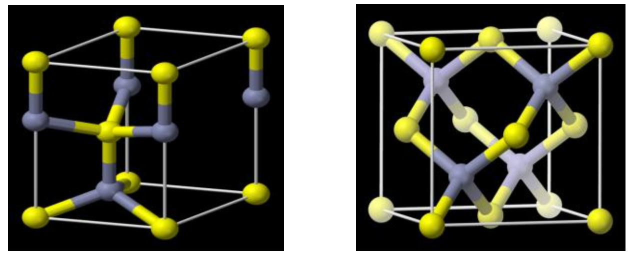
$$E_G(T) = E_G(0) - \frac{\alpha . T^2}{(T+\beta)} \quad , \qquad (1),$$

Where α and β are coefficients. If T is measured in K, bandgap is in electron volts (eV).

GaN is grown in Wurtzite crystal structure, or in Zinc-blende crystal structure. Obviously, the band gap, Eg, is affected by the crystal structure. The Wurtzite Crystal Structure, and the Zinc-blende crystal structure are shown below.

In case of the Wurtzite crystal structure, it has been observed that it has an ideal angle of 109° and the nearest neif\ghbour at 19.5 nm, and has been found to be energetically favorable. It has to be noted that this structure is also observed in other semiconductors, like Agl, ZnO, CdS, and CdSe,

In case of the Zinc-blende Crystal Structure, it has an ideal angle of 109.47^0, Energy gap of 3.2 eV, and the nearest neighbor at 19.5 nm.



(a) **(b)**

FIGURE 1. (a) Wurtzite crystal structure of GaN, (b) Zinc-blende crystal structure of GaN, Figure courtesy. http://en.wikipedia.org/wiki/Image:Wurtzite-unit-cell-3D-balls.png.

The GaN Bonding Properties are given below:

(i)Tetrahedral bonds – with sp^3 hybridization, Bonding angle: 109.47°, and the Bond Length = 19.5 nm.

(ii) Ga-N bonds are significantly stronger than Ga-Ga interactions (based on distance).

GaN shows the mixed ionic-covalent bonding - Ionicity of a bond is the fraction f_i of ionic character compared to the fraction of f_h of covalent character. The Modern definition is the ionicity phase angle. The Electronegativity, denoted by the symbol χ, is a chemical property, which defines the tendency of an atom or a functional group to attract electrons (or electron density) towards itself The percentage of the ionic character I a function of the electronegativity difference, and is found to increase with increase in the electronegativity difference. The behaviour of the curve showing the dependence of percentage of ionic character on the electronegativity difference is as shown below:

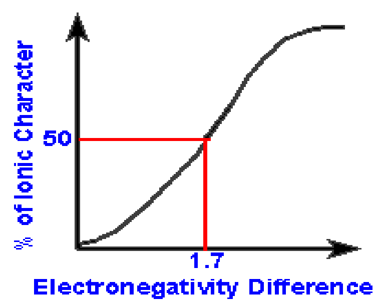


FiGURE 2. Ionic character as a function of the Electronegativity Difference. Figure courtesy. http://www.bcpl.net/~kdrews/bonding/bonding2.html.

The fraction of ionic character f_i is empirically given by the following relation:

$$f_i = [1 - e^{\frac{(X_A - X_B)2}{4}}]. \qquad (2)$$

Where (X_A - X_B) is the difference in electronegativity between the atoms A and B.

The GaN Bonding Properties based on calculations using both methods are as: Pauling ionicity and Modern ionicty are respectively 0.387 and 0.500. Bond Character is dependent on electronegativity, and varies are as given below:

$$\chi_N >> \chi_P > \chi_{As} > \chi_{Sb}$$

The Bonding strength determines energy gap size, and the large band gap is the evidence of strong bonding in GaN. The parameters for some of the Strongly Ionic Compounds (also insulators) are:

LiF – 11eV; NaCl – 8.5eV; KBr – 7.5 eV.

For some III-V compounds, the values are as: GaN – 3.2 eV/3.4 eV, GaP – 2.3 eV, AlSb – 1.5 eV, and InP – 1.3 eV.

II. USE OF THE INTERDEPENDENCE OF PARAMETERS IN DESIGNING OF GaN DEVICES

It is very important to understand and consider the Interdependence of Parameters of the various GaN Material Parameters, while designing the devices.

A. Temperature dependence of bandgap energy

The energy gap (eV) dependence on temperature has been studied by a number of workers in various academic and industrial institutions, It is found to fit in the following equation:

$$E_g(eV) = 3.396 + 9.39\times10^{-4}\cdot[\frac{300^2}{300+772} - \frac{T^2}{T+772}] \ . \qquad (3)$$

B. Density of states for GaN

The density of states in a semiconductor is the density per unit volume, and energy of the number of solutions to Schrödinger's equation. It is assumed that the semiconductor is modeled as an infinite quantum well in which electrons with effective mass, m^*, can move freely, the energy in the wellbeing set to zero. The results of the experiments of the workers in various academic and industrial institutions are quite similar, and the established variations for the parameters $N_C(T)$ and $N_V(T)$ representing respectively the density states for the conduction band and valence band as a function of temperature (in K) are given empirically by the following expressions:

$$N_C(T) = 2\left(\frac{2\pi m_e^* kT}{h^2}\right)^{\frac{3}{2}} = 2.50945\times10^{19}\cdot\left(\frac{m_e^*}{m_0}\right)^{\frac{3}{2}}\left(\frac{T}{300}\right)^{\frac{3}{2}},$$

$$N_V(T) = 2\left(\frac{2\pi m_h^* kT}{h^2}\right)^{\frac{3}{2}} = 2.50945\times10^{19}\cdot\left(\frac{m_h^*}{m_0}\right)^{\frac{3}{2}}\left(\frac{T}{300}\right)^{\frac{3}{2}}, \quad (4)$$

where k is wavenumber, h is the Planck's constant, T is the temperature (in K), m_c^* and m_h^* are density-of-state effective masses of electrons and holes, m_0^* is the free effective mass of electron, E_c and E_v are energies of the bottom of the conduction band and the top of the valence band, respectively, and h is Planck's constant.

Also, the corresponding computed values at $300^\circ C$ K are given below:

$$N_C(300) = 2.3\times10^{18}, \ m_e^* = 0.20\ m_0 \text{ for Wurztite GaN},$$

$$N_V(300) = 4.6\times10^{19}, \ m_h^* = 1.50\ m_0 \text{ for Wurztite GaN.} \qquad (5)$$

C. Incomplete ionization of impurity atoms

The ionization of the impurity atoms has also to be taken care of, while designing the devices. The accepted dependences are given by the following expressions:

$$N_D^+ = \frac{N_D}{[1+g_B\cdot\exp\left(\frac{E_{Fn}-E_C+\Delta E_D}{kT}\right)]}, \quad \Delta E_D = 0.016 \text{ eV for Si},$$

$$N_A^+ = \frac{N_A}{[1+g_B\cdot\exp\left(\frac{E_V-E_{Fp}+\Delta E_A}{kT}\right)]}, \quad \Delta E_A = 0.175 \text{ eV for Mg}, \quad (6)$$

where $N_D{}^*$ and $N_A{}^*$ are concentrations of ionized donors and acceptors, respectively If N_D>N_A, the semiconductor is of is of n-type.

D. Intrinsic carrier concentration

Te intrinsic carrier concentration

$$n_i(T) = \sqrt{N_C\cdot N_V}\cdot\exp(-\frac{E_g}{2kT}), \qquad (7)$$

and its numerical values for T and T=300 are given below:

$$n_i(T) = 1.98\times10^{16}\cdot T^{\frac{3}{2}}\cdot\exp(-\frac{20488}{T}), \qquad (8)$$

and

$$n_i(300) = 2.25\times10^{-10} cm^{-3} \quad \text{for epitaxial GaN}. \qquad (9)$$

The small intrinsic carrier concentration in GaN at room temperature enables the high power and temperature applications.

E. Mobility and recombination models

The electron mobility μ is defined as

$$\mu = \frac{v_d}{E},$$

where E is an electric field applied across a piece of material, for which the electrons respond by moving with an average velocity called the drift velocity v_d.

The Mobility Models (a and b) and Recombination Models (c and d) are also considred in the designing and fabrication of the devices. These are as: (a) Analytical Mobility Model, (b) Field-Dependent Mobility Model. These are respectively given as:

$$\mu = \mu_{\min} + \frac{\mu_{\max} \left(\frac{T}{300}\right)^{\alpha} - \mu_{\min}}{1 + \left(\frac{T}{300}\right)^{\beta} \left(\frac{N_{tot}}{N_{ref}}\right)^{\gamma}}, \quad (10)$$

and

$$\mu_n(E) = \frac{\mu_n}{\left[1 + \left(\frac{\mu_n E}{v_{sat}}\right)^{\beta_i}\right]^{1/\beta_i}}. \quad (11)$$

We know that the carrier generation and recombination results from the interaction between electrons and other carriers, with the lattice of the material, or with the optical photons. Due to the electron movement from one energy band to another, it gains or loses energy, in some other form, which distinguishes different types of generation and recombination. In the Shockley–Read–Hall (SRH) process, the electron in transition between bands passes through a new energy state created within the band gap by an impurity in the lattice - Localized State, which can absorb differences in momentum between the carriers, and hence this process is the dominant generation and recombination process in the indirect bandgap materials. In case of the Auger recombination, the energy is given to a third carrier, excited to a higher energy level without moving to another energy band, which after the interaction, normally loses its excess energy to thermal vibrations. Since the third particle has to begin the process in the unstable high-energy state, the Auger effect process is not easily produced.

The parameters - Shockley-Read-Hall Recombination (R_{SRH}) and (d) Auger Recombination (R_{Ar}) are respectively given as;

$$R_{SRH} = \frac{p \cdot n - n_i^2}{\tau_p (n + n_i) + \tau_n (p + n_i)},$$

$$\tau_n = \frac{\tau_{n0}}{1 + \left(\frac{N_{tot}}{N_n^{SRH}}\right)^{\gamma_{ns}}},$$

and

$$R_{Au} = (C_p p + C_n n)(n \cdot p - n_i^2). \quad (12)$$

where τ_p and τ_n are the life times of the carriers respectively for p type and n type (each being ~ 1 nanosecond).

Thus we see that the designing of the devices based on the GaN is a very specialized job. The interdependence of many parameters, and also their dependences on other parameters like temperature, E_c and E_v has to be considered. Though, software for this work is available, still the optimum design can be made only by a specialist designer. In addition to this, the technologist has to produce the optimized results with a high degree of repeatability. Often, they have to work as a team, because the achieved results are considerably different from those expected on the basis of computations, the final results being dependent on the feedback of the measurements, and the experience of the designers and technologists for applying corrections.

III. GaN BASED DEVICES

GaN is a binary III/V direct bandgap semiconductor, which has been commonly employed in bright light-emitting diodes during the last two decades. The compound has a Wurtzite crystal structure, and is a very hard material. The fact that it has wide band gap of 3.4 eV, is responsible for its special properties for applications in optoelectronic, high-power and high-frequency devices. Also, the GaN substrate can be used for making violet (405 nm) laser diodes, even without using the nonlinear optical frequency-doubling. As is the case with nitrides of all group III elements, it possesses low sensitivity to ionizing radiation, and hence is very suitable material for solar cell arrays used in satellites. Besides, having stability in radiation environments, it is very useful for the Military and space applications. Another useful characteristic is that GaN transistors can operate at much higher temperatures and at much higher voltages than GaAs transistors, and hence are employed for making the ideal power amplifiers at microwave frequencies.

Due to the fact that GaN has very high breakdown voltages, and high electron mobility and saturation velocity, it is an ideal candidate for high power and high temperature microwave applications, like the microwave RF power amplifiers, and high voltage switching devices for power grids. Also, the GaN-based RF transistors are used as the microwave source for microwave ovens. Its large band gap ensures that the performance of GaN transistors is maintained up to higher temperatures than the silicon transistors. Already, the GaN based Schottky rectifiers with ultrafast reverse recovery characteristics, and UV photodetectors with ultralow dark currents have been developed. Some safety precautions have to be taken, as the GaN dust is an irritant to skin, eyes and lungs. However, the bulk GaN is non toxic and biocompatible, and therefore, can be used in the electrodes and electronics of implants in living organisms.

GaN is very much in use in various applications, and some of the typical applications are:(i) New Kind of Nanotube, (ii) Laser diodes, (iii) High-resolution Printings, (iv) (v) Solar Cells, and (v) Microwave radio-frequency power amplifiers,

The New Kind of Nanotube is in the form of Single Crystal Nanotube, which is fabricated by using GaN. The Gallium Nitride nanotubes have diameter between 30 – 200 nm, and have the potential for mimicking ion channels. The Gallium Nitride nanotube is as shown below:

FIGURE 3(a). Gallium Nitride nanotube.

The GaN Laser Diode has the properties: Normally emits the ultraviolet radiation, Indium doping allows variation in band gap size, and the Band gap energies range from 0.7eV – 3.4eV. The Gallium Nitride Laser Diode is as shown below:

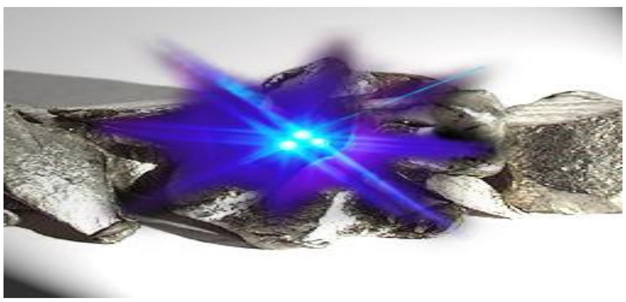


FIGURE 3(b). Gallium Nitride Laser Diode. Figure courtesy. http://www.lbl.gov/Science-Articles/Archive/assets/images/2002/Dec-17-2002/indium_LED.jpg.

These GaN Laser Diodes have Applications in: 'Blu-Ray' technology, and Laser Printing.

The GaN Solar Cells have the properties: Indium doped (InGaN), Conversion of many wavelengths for energy, Theoretical 70% maximum conversion rate, Multiple layers attain higher efficiency (Need many layers to attain 70%), and Lattice matching not an issue. They have various advantages as: High heat capacity, Resistant to effects of strong radiation, and High efficiency. However, there are certain difficulties: Too many crystal layers lead to the system damaging stress, and are very expensive.The GaN High Power Rectifiers are based on various properties: High Temperature, High Power and High Frequency Applications, Intrinsic wide bandgap energy, High breakdown field for the case of the power applications, Very good electron transport properties, Heterostructure availability and strong piezoelectric polarization effect.

Fabrication of the GaN high power rectifiers (GaN Schottky and PiN rectifiers) mainly involves the steps: (i) GaN epi layer on sapphire, and (ii) GaN epi layer on freestanding GaN, in the Vertical geometry. The device processing is based on: Mesa etch (ICP dry etch), Oxide deposition (PECVD), p-guard rings (Implantation), Window opening (RIE), Ohmic metal formation (RTA), and Schottky metal deposition (E-beam). The GaN Schottky Diode Array, is shown below

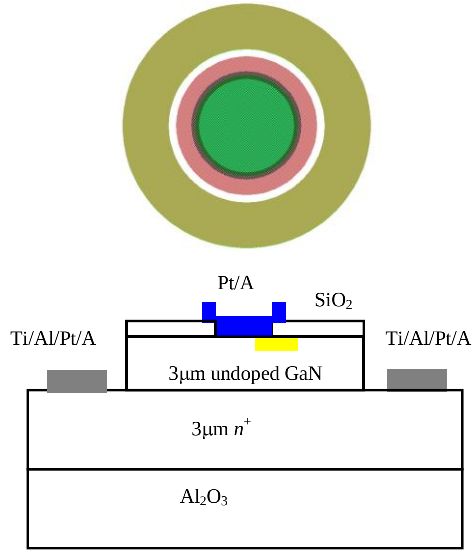


FIGURE 4. Schottky diode array with the size of 500 µm x 500 µm. Figure courtesy. http://www.shef.ac.uk/polopoly_fs/1.119646!/image/sm1.jpg

The Schottky diode array with the size of 500 µm×500 µm, has nitride windows interconnected with electroplated Au (~3µm). It has 161 A forward output current at 7.12 V, R_{ON} (On-state resistance) = 8 mΩ·cm^2, 1.1 kW for 6×6 mm^2 (active device area). Already, some promising results for practical on-state current, have been achieved, and are very close to the simulated R_{ON} values (3.3 mΩ·cm^2).

IV. QUALITATIVE REVIEW OF SOME RECENT NOVEL APPLICATIONS AND CONCLUDING RRMARKS

The important features and benefits of GaN as a material for the device fabrication are: High frequencies, bandwidth up to 6 GHz, High efficiencies, High power density, High thermal conductivity, and Excellent ruggedness. As a result of these characteristics, GaN can operate at high temperatures, without loss of reliability (250 °C compared to 225 °C for Si LDMOS). Therefore, it has many important applications: Commercial wireless infrastructure (base stations), Radar systems, Broadband and narrow band general purpose amplifiers, Industrial /Scientific Medical Instruments, Jammers and EMC testing. It is finding new applications in Defence and aerospace sectors and also Consumer electronics. With the increasing realization of the advantages of GaN over GaAs, there has been a spurt of studies [10, 11, 12, 13, 14] on exploring the Novel Applications of GaN based devices. Wang *et al.* [15] have investigated the optical joint densities of states of three InGaN/GaN-based light-emitting diodes with different emission wavelengths (violet, blue and green) operated at various currents, and their results have indicated that the blue shift of the emission with increasing current is related to the variation in optical joint density of states. They have ascribed the blue shift to the screening of the piezoelectric field by carriers. They have also found a tail at the low-energy end of the density of states, corresponding to localized states, and have emphasized that the presence of these tails broadens the spectra of the devices.

Wang [16] has described the research on the fabrication and characterization of Gallium nitride (GaN) based diodes. He has emphasized that because of its direct wide bandgap and outstanding electric properties, GaN is widely used in solid state lighting applications and considered as an alternative to Silicon in power electronics devices. He has fabricated (i) high performance GaN based Schottky diodes by using n- bulk GaN substrates synthesized by Hydride Vapor Phase Epitaxy (HVPE) process. By depositing full back ohmic contact on the N face and circular Schottky contacts on the Ga face, it has been shown that the Schottky diodes possess excellent forward and reverse bias characteristics, and thus result in a high figure of merit (FOM); (ii) GaN Schottky diodes on n- epilayer/ n+ bulk GaN structure, by depositing the epilayers using Metal-Organic Chemical Vapor Deposition (MOCVD) on HVPE grown substrate. The devices have been reported to have shown very high breakdown voltages. Also, the electrical measurements like current-voltage (I-V) and capacitance-voltage (C-V) have been made to extract ideality factors, series resistance and other important parameters from the diode, besides carrying out the Raman spectroscopy to determine the average junction temperature of the commercial ultraviolet (UV) light emitting diodes (LEDs). These results are expected to have important impact on the development of novel devices with increased efficiency. Felbinger *et al*. [17] have reported the growth, fabrication, and performance of AlGaN/AlN/GaN high-electron-mobility transistors (HEMTs) with a total barrier thickness of 7 nm. They have discussed that (i) an optimized surface passivation and an Ohmic recess etch yield HEMTs exhibiting 0.72 S/mm peak extrinsic DC trans conductance at a current density of 0.47 A/mm, and (ii) the devices with a gate length of 90 nm achieve 78 GHz unity-current-gain frequency and up to 166 GHz maximum frequency of oscillation. It has been reported that the minimum noise figure at 10 GHz is 0.52 dB with an associated gain of 9.5 dB.

Hoffmann *et al*. [18] have investigated the growth, fabrication, and properties of GaN/AlN/sapphire with periodically poled surface polarity for second harmonic generation, and have achieved the periodic inversion of the surface polarity by the growth of a thin AlN buffer layer and subsequent partial removal by using either wet etching with potassium hydroxide (KOH) or reactive-ion etching (RIE). It has been emphasized that the GaN growth on these substrates by MOCVD leads to Gapolar GaN on the AlN buffer and N-polar GaN on the bare sapphire. By using the atomic force microscopy and scanning electron microscopy, they have demonstrated that a sufficient combination of H_2 and NH_3 surface treatment before the growth of the GaN layers removes surface defects introduced by the RIE etching, which implies that the films with comparable quality and properties independent of the etching technique can be grown. It has, however, been noticed that, in contrast to the RIE etching, the interfaces between the Ga-polar and N-polar GaN are rough if KOH etching is applied, and hence it has been concluded that MOCVD in combination with RIE etched AlN/sapphire substrates can be a versatile process to fabricate GaN with periodically poled surface polarity as desired for the UV light generation by frequency doubling. Mehandru *et al*. [19] have used a finite element simulation to quantitatively estimate the effectiveness of flip-chip bonding in the temperature rise of bulk GaN Schottky rectifiers under various conditions of current density, duty cycle, forward turn-on voltage and on-state resistance, by keeping the temperature difference between flip-chip bonded devices and bottom bonded devices = 20 °C even at modest current densities. They have reported that the maximum temperature in the bulk cases occurred in the center of the GaN substrate thickness, and the transit time of the temperature reaching the steady state for the flip-chip bonding device is in the range of millisecond, which is faster than that of most power switch applications. It has been suggested that the Flip-chip bonding can improve the heat dissipation of high power, bulk GaN rectifiers. The realization of the importance of the GaN technology can be seen from the fact that very recently, the 2014 EMN Spring Meeting has taken place [20], where many aspects of the technology and the devices based on this, in addition to many other topics including quantum dots and semiconductor nanowires have been discussed. Thus, it is seen that GaN, in addition to being useful in itself for various applications, can be tailored to provide some novel results, and hence it can be safely concluded that the technology is evolving, and is on a firm footing for finding novel applications.

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