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(Invited) Material Considerations for the Development of III-nitride Power Devices

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With advancement in growth of native III-nitride substrates, remarkable progress has been made to extend the functionality of GaN based power electronic devices. The low dislocation epitaxial films grown on native substrates outperforms the films grown on foreign substrates. However, several material considerations has to be incorporated in order to exploit the full potential of GaN and $Al_xGa_{1-x}N$ ($0<x\leq1$) based power devices. This paper presents a review report on the development of III-nitride power devices grown on foreign and native (GaN and AlN) substrates. Discussion on state-of-the art epitaxial material quality, contact formation and surface treatments films are presented.

I. Introduction

III-nitride electronics has gained a significant attention toward different power electronic applications, since they offer a significant improvement in the figure of merit (FOM) as compared to other semiconductor systems like SiC or Si (1,2). As such, GaN based electronics has gained enough maturity, and has been commercialized by many vendors (3). GaN devices have been shown to be radiation tolerant making them suitable for being used in space applications (4). However, there are several issues that currently impede performance of vertical GaN and AlN power electronics that preclude commercialization and require to be solved.

AlN and GaN are typically grown by hetero-epitaxy on foreign substrates (Si, SiC or sapphire substrates) which necessitate lateral power electronics instead of the preferred vertical geometry on power devices (5). Going to the lateral device configuration, they suffer from several challenges like: (i) requirement of a high die area to achieve a high breakdown voltage; (ii) trapping effect at the surface degrades the performance, among others. Recently, vertical III-nitride devices grown on native substrates has been demonstrated to achieve a lower die area, reduced surface trapping effects, and a higher vertical current density (3). Further, the hetero-epitaxial films exhibit a high dislocation densities of the order 10^9 to 10^{10} cm^{-2} due to large lattice mismatch with the foreign substrates (6). Hence, growth on native substrate (with dislocation densities 10^3 to 10^6 cm^{-2}) is highly desired for high quality and low defect density homo-epitaxy to produce vertical power devices (7,8). With advancement and availability of bulk native substrates, III-nitride devices made on native substrates is providing several pathways for performance improvement in next generation power devices.

This paper describes several materials consideration to develop power Schottky diodes on native GaN and AlN substrates. Section II highlights a brief background of III-nitride power devices and their corresponding requirements. Section III presents the materials consideration for GaN power devices made on foreign and native GaN substrates. Alongside, a discussion is presented on point defect control that can be used to enhance the carrier mobility by reducing the compensating defects in the GaN epitaxial film. Going beyond the GaN based electronics, recent reports also predict further performance improvements by moving into $Al_xGa_{1-x}N$ ($0<x\leq 1$) based power devices (9). Thus, section IV is dedicated to material considerations for $Al_xGa_{1-x}N$ ($0<x\leq 1$) based power devices necessary to further exploit the functionality of entire III-nitride spectrum.

II. A brief background on III-nitride power devices

Schottky contacts serve as the core of most of the high-power devices. Schottky barrier diodes which are highly used in high frequency switches, consists of a drift layer, an ohmic contact and a Schottky contact which controls the ON/OFF state of the diode (10). A forward biased Schottky contact allows current to flow between the contacts resulting in the ON state of the diode. Similarly, the Schottky contact can be reverse biased to achieve the OFF state. To obtain a better FOM, a thick drift layer with low free carrier concentration and high carrier mobility is required in the epitaxial GaN film. A lower dopant concentration results in a high reverse breakdown field of the semiconductor, whereas a high mobility is desired to achieve lower ON resistance.

On the other hand, high electron mobility transistors (HEMTs) which are highly used in microwave/RF power amplifiers, are typically made of the AlGaN/GaN heterostructure (2). The difference of spontaneous polarization charge between GaN and AlGaN induces a two-dimensional electron gas (2DEG) at the AlGaN/GaN interface (11). The transistor consists of source and drain connected by the 2DEG, and a Schottky metal gate is used to deplete the 2DEG thereby cutting-off the channel region. Note that a gate bias is required to deplete the channel, and hence most of the HEMTs are normally-ON devices. Several structures have been proposed to realize normally-OFF HEMTs (3). Also, planar AlGaN/GaN HEMTs do not require doping, since the polarization field creates 2DEG between the source and drain. Recent studied also highlight the advantages of vertical power transistors over the traditional planar HEMTs (3). In lateral HEMTs, a higher die area is necessary to achieve a higher breakdown voltage, whereas the breakdown voltage is independent of die area in case of vertical HEMTs. Similarly, the lateral HEMTs have high electric field near the surface, and charge trapping at the interface degrades the performance. Contrary to this, the surface is located far away from the high electric field regions in the case of vertical HEMTs.

III. Material considerations for GaN power devices

Although mobility increases with reduction in free carrier density due to lower ionized impurity scattering, the electron mobility decreases drastically with a further decrease in the concentration of free electrons $<10^{17}$ cm^{-3}. This is primarily due to residual carbon as impurity of the order of 10^{17}-10^{18} cm^{-3} acting as compensator in the epitaxial film (12). The C incorporation originates from the splitting of the metal organic precursors. When the Si doping concentration is much higher than the typical carbon concentration, the compensation is insignificant for the electron mobility. However, as the Si doping concentration becomes comparable to the carbon compensation limit, the residual carbon impurity strongly influences the mobility of the free electrons. When the concentration of compensating C defects is not reduced by implementing specific epitaxial process conditions, a free carrier concentration of 10^{17} cm^{-3} or lower yields a mobility of only 100 cm^2/Vs or lower, which can result in a very poor FOM. Thus, techniques have been developed to mitigate the residual carbon impurity by increasing the Ga-supersaturation during the growth. Following this approach, the total C concentration can be controlled over more than 4 orders of magnitude, down to values as low as $2\text{x}10^{15}$ cm^{-3} (12). As a result, GaN films with free carrier concentration between $1\text{x}10^{16}$ cm^{-3} to $5\text{x}10^{16}$ cm^{-3} resulted in bulk mobilities between 720 cm^2/Vs and 1170 cm^2/Vs. In order to achieve an attractive growth rate for thick drift layers, alternative defect control methods such as defect quasi Fermi level control have been recently explored. By injecting minority carriers through above-bandgap illumination during epitaxy, the concentration of compensating defects could be further reduced (13). This method is currently used to manufacture drift layers for vertical power devices.

Apart from point defects arising from the doping activity, mobility is also degraded by the threading dislocations in the epitaxial film (14). Traditionally, GaN is grown on sapphire substrates with dislocation density of 10^8-10^{10} cm^{-2}. As a result, the epitaxial film has threading dislocation of the similar order. Threading dislocations are detrimental to mobility of the free carriers as some of these defects are charged and acts as a coulomb scattering center (14). Thus, a way to get rid of this scattering is to achieve films with lower dislocation density. This is achieved by growing films on GaN native substrates (5). Kyle *et al.* has shown that mobility decreases significantly with increase in threading dislocation density (15). Thus, growing GaN on native substrate with dislocation density in the order of 10^6 cm^{-2} resulted in a mobility of 1265 cm^2/V s for a free carrier concentration of the order 10^{16} cm^{-3}. Furthermore, lateral Schottky diodes made on native GaN substrate has been reported to show significantly lower leakage current compared to diodes made on foreign substrate (7). A lower threading dislocation density in epitaxial films grown on native GaN substrates suppresses the trap/defect assisted tunneling and hopping conduction resulting in a significantly reduced reverse leakage current. Finally, free carrier concentration in the range of low 10^{15} cm^{-3} has been achieved recently in GaN epitaxial films grown on native GaN substrates (16,17). All these point toward obtaining power Schottky diodes with excellent FOM when grown on native GaN substrates. Along the same line, availability of native GaN substrate has helped in obtaining vertical power transistors where drain can be put on the back side of the wafer. Consequently, the current transport from source to drain is vertical resulting in a much higher current capability than planar power transistors (3).

Finally, the GaN Schottky contact interface also plays a critical role in determining the performance of power devices. A Schottky diode suffers from higher reverse leakage and degraded ideality factor when the Schottky contact comprises of interface states (18). GaN Schottky diodes show varying ideality factors in the range of 1.2-1.8, with a reverse leakage current varying over several orders of magnitude. Consequently, the breakdown voltages of GaN Schottky diodes are limited to sub-kV due to surface instabilities. Surface states induced during the photolithography process is one of the component of the surface instabilities. GaN surface is exposed to photoresists and developed in Tetra-methyl ammonium hydroxide (TMAH) in most cases. X-ray photoelectron spectroscopy (XPS) studies revealed the change in GaN surface from Ga-rich (Ga to N ratio ~1.3) to a nearly stoichiometric (Ga to N ratio ~1) as a result of a chemical reaction between GaN and the TMAH. Alongside, a significant presence of carbon at the GaN surface has also been detected by XPS after the photolithography process. The resulting interfacial phases is likely to introduce inhomogeneity with parallel leakage paths across the barrier. Consequently, an acid based surface treatment after the photolithography process and before depositing the Schottky contact metal restored the original surface resulting in a nearly defect free and ideal barrier performance. Interestingly, Cao *et al.* has also reported 2-5 orders of magnitude decrease in reverse current in Schottky diode by lowering the carbon impurity in the epitaxial film (16). All these points toward importance of controlling the carbon impurity during the epitaxial film growth, as well as during the contact formation. Table I summarizes some of the recent reports on improving the reverse leakage current in Schottky diodes.

TABLE I. Recent Reports on Improving the Reverse Leakage Current in Schottky Diodes.

Condition	Substrate	Reduction in I_{off}	Remarks
Effect of carbon impurity in the epitaxial film	GaN	2-5 orders of magnitude	Reference sample has ~4 orders of magnitude more carbon in the epitaxial film (16).
AlGaN/GaN lateral Schottky barrier diode	GaN	~5 orders of magnitude	Reference sample was grown on sapphire substrate (7).
Effect of low doping concentration	GaN	>3 orders of magnitude	Reference sample has nearly an order of magnitude higher carrier concentration (17).
Effect of surface treatment after photolithography	Sapphire	>4 orders of magnitude	Reference sample had no chemical treatment to restore the surface (18).

III. Material consideration for $Al_xGa_{1-x}N$ ($0<x\leq1$) power devices

Since FOM scales with third power of critical electric field (E_c) of the semiconductor, Al-rich AlGaN and AlN offers a wider bandgap than GaN, and hence a better E_c compared to any other competitive candidates. Coltrin *et al.* has recently reported that $Al_xGa_{1-x}N$ devices have better FOM than GaN devices at room temperature for $x\geq0.72$, whereas at elevated temperature, $Al_xGa_{1-x}N$ power devices outperforms the GaN devices for $x\geq0.57$ (9). For room temperature operation, it is further forecasted that AlN based Schottky diodes will have 15 times higher power handling capacity to that of GaN based Schottky diodes (19). Thus, understanding the material considerations associated with $Al_xGa_{1-x}N$ ($0<x\leq1$) devices is necessary to meet the future power device requirements.

Similar to GaN, AlGaN films grown on foreign substrates also result in significant lattice mismatch resulting in high dislocation densities (20). As a result, the conductivity of the AlGaN epitaxial films grown on foreign substrate is highly degraded. Films with lower dislocation densities achieve better conductivity along with reduced carrier trapping and compensation (21). The development of single crystal AlN substrates with dislocation densities < 10^3 cm^{-2} has made it possible to grow excellent quality Al-rich AlGaN films with low densities of extended defects (8,36,37). However, a high activation energy and high compensation in Al-rich AlGaN films result in a fraction of dopants (Si) atoms contributing free carriers (22,23). Thus, the free carrier concentration in Al-rich AlGaN is several orders of magnitude lower than the doping concentration. Consequently, the ratio of resistivity of $Al_xGa_{1-x}N$ films increases by several orders of magnitude when x increase from 0.8 to 1 (22). Such a large difference between the free carrier concentration and doping density can be detrimental for power devices. The exact nature of compensating defects is still not clear, but many reports suggest compensation due to carbon, oxygen, and vacancy related defects play a major role in compensating the dopants (22-24). Collazo *et al.* has reported significant reduction in resistivity for Al-rich AlGaN layer when grown on single crystal AlN substrates compared to the sapphire substrate (23). Further research is necessary to understand the defect incorporation in Al-rich AlGaN films grown on native AlN substrates. Hence, apart from reducing the dislocation densities, identifying the compensators and eliminating them is necessary to exploit the full potential of AlGaN and AlN power devices.

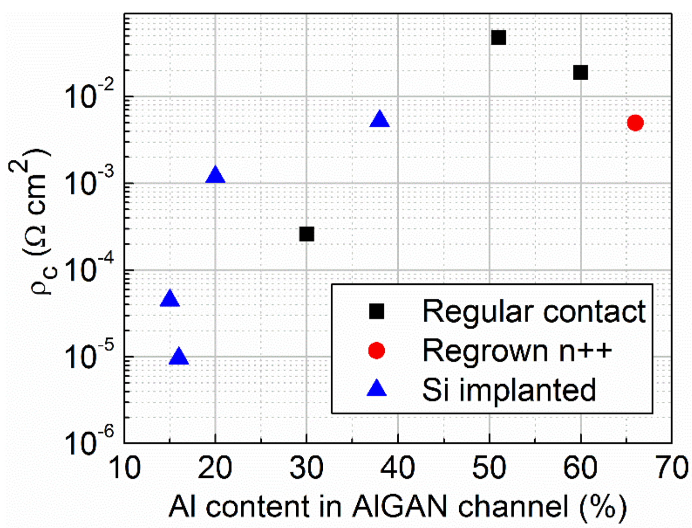

Figure 1. Specific contact resistance (ρ_c) obtained for different AlGaN channel HEMTs (25-32). Regular contact means ohmic contact metallization directly applied to $Al_yGa_{1-y}N/Al_xGa_{1-x}N$ HEMTs (y>x).

Another prime concern of Al-rich AlGaN devices is the formation of ohmic contacts. Typical contact metallization schemes which form ohmic contact with GaN or Ga-rich AlGaN, shows the presence of a Schottky barrier at the metal-AlGaN interface (25). As a result, contact formed directly on Al-rich AlGaN layer of HEMTs show a very high contact resistance (28). A summary of specific contact resistance obtained in different AlGaN channel HEMTs is shown in Figure 1. As observed in Figure 1, the specific contact resistance increases significantly with the increase in Al% of the AlGaN channel. Several approaches has been developed to achieve a better contact formation to AlGaN channel HEMTs. For example, Nanjo *et al.* reported implanting the AlGaN layer with Si for ohmic contact formation (30). Similarly, Douglas *et al.* reported re-growth of an highly doped GaN layer on recessed AlGaN channel to achieve a low contact resistance (25). Bajaj *et al.* reported growth of a doped AlGaN graded layer for ohmic contact formation in the Al-rich AlGaN channel transistor (33). In this technique, a graded layer (Al-rich to Ga-rich AlGaN) is grown on Al-rich AlGaN channel allowing the formation of a low resistive ohmic contact to Ga-rich AlGaN.

Note that the approach to contact doped or implanted AlGaN layers requires a high free carrier concentration in order to achieve a low contact resistance (34). Growth of AlGaN channel devices on native substrates is thus desirable to meet this criteria. Although growing Al-rich AlGaN on single crystal AlN substrate result in orders of magnitude higher carrier concentration than foreign substrates, but traditional Ti/Al or V/Al based ohmic contact shows a nonlinear current-voltage characteristics (34,35). A higher dislocation density in $Al_xGa_{1-x}N$ (x=0.6) films grown on sapphire substrates support significant Frenkel-Poole trap assisted tunneling (F-P TAT) at low bias voltages resulting in formation of ohmic contact. However, the ohmic behavior is lost as the concentration of Al in AlGaN is further increased. On the other hand, the absence of defects in $Al_xGa_{1-x}N$ (x=0.6) films grown on single crystal AlN substrate restricts the F-P TAT current at low bias. Hence, the contacts to Al-rich AlGaN are highly nonlinear and resistive at low bias voltages. Recently, reactive ion etching (RIE) based surface treatment before contact metallization resulted in ~4 orders of magnitude decrease in the contact resistance to Al-rich AlGaN (34). Reduction of barrier height at the free surface and introduction of defects after the RIE surface treatment is thought to accompany a higher current at low bias voltages. All these point toward development of further optimization techniques necessary to exploit the performance improvement in $Al_xGa_{1-x}N$ ($0<x\leq1$) channel power devices.

IV. Conclusions

In conclusion, this paper provides a brief review of current issues with GaN and $Al_xGa_{1-x}N$ ($0<x\leq1$) based power devices. Material considerations such as growth on native substrates, control of compensating point defects, study of contact formation, etc. is necessary to obtain high performance power devices to meet the future power saving needs. Although GaN technology is matured enough and has been successfully commercialized for several applications, a better figure of merit can be obtained by moving into $Al_xGa_{1-x}N$ ($0<x\leq1$) based power devices. With advancement in availability of native substrates, exploring the

III-nitride power devices grown on native substrates can provide significant improvement in performance in future power devices.

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