Degradation Mechanisms of GaN Based Microwave Devices

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Abstract

Wide bandgap semiconductors are extremely attractive for the gamut of power electronics applications from power conditioning to microwave transmitters for communications and radar. Of the various materials and device technologies, the AlGaN/GaN high-electron mobility transistor seems to be the most promising. While GaN device and circuit technology is poised to break out in the commercial arena, certain risks or barriers to entry in the market should not be overlooked. The relative technology immaturity of GaN with respect to Silicon and GaAs leave issues like long-term reliability unanswered. This paper reviews the main degradation mechanisms of GaN-based HEMTs devices.

Introduction

The properties of Ill-V nitride heterostructures are attracting increasing attention for a wide range of device applications, including blue, green, and ultraviolet LED's, short wavelength lasers, and high power, high temperature, and high frequency electronic devices. There are three important binary nitride materials: AIN, GaN, and InN. Among these, GaN shows great promise for microwave applications. The wide energy bandgap of GaN (3.43 eV, as compared to 1.4 eV for GaAs) leads to low intrinsic carrier concentration over a wide range of temperatures. This in turn allows GaN based devices to be operable at high temperatures. Also this wide bandgap allows very high electric breakdown fields (1.5 x 10^7 V/m as compared to 2.5 x 10^5 V/m for GaAs). As a result GaN based devices can be biased at very high drain voltages (breakdown voltage = 50 - 500 V depending on the application), and because of the large thermal conductivity of GaN (1.7 W/cm.K as compared to 0.46 W/ cm.K for GaAs), the channel temperature can reach 300 °C.

Even though the low-field mobility is not high (the best value reported so far for GaN is about 2000 cm^2/V.s as compared to a value about 8500 cm^2/V.s for GaAs), it is not very sensitive to ionized impurity concentration. Furthermore, a larger peak velocity can be reached (2.7 x 10^7 cm/s at room temperature as compared to 1.5 x 10^7 cm/s for GaAs), which permits high currents and high operating frequencies. The energy bandgap difference between AIN and GaN is also quite significant (e.g 2.57 eV, as compared to 0.73 eV for GaAs and AlAs), which permits high concentrations of free carriers to be confined at the AlGaN/GaN heterointerface paving the way for the high performance AlGaN/GaN high electron mobility transistor [1].

GaN-based microwave power HEMTs have defined the state-of-the art for output power density and have the potential to replace GaAs-based transistors for a number of high-power applications. The GaN-based material system, consisting of GaN, AlN, InN and their alloys, has become the basis of an advanced, microwave-power-device technology for a number of reasons. GaN has a breakdown field that is estimated to be 3 MV/cm, which is ten times larger than that of GaAs, and a high peak electron velocity of 2.7×10^7cm/s. In addition, this material system is capable of supporting a heterostructure device technology with a high two-dimensional electron gas (2-DEG) carrier density and mobility. As a result of these properties, excellent high-frequency, high-power performance has been achieved with GaN-based HEMTs. Although significant progress has been made in the past few years, additional developmental work is required for GaN HEMTs to become a viable technology. One area of active research deals with the reduction of trap effects in GaN-based devices. Historically, a variety of trap effects have been observed. These include transconductance frequency dispersion, current collapse of the drain characteristics, light sensitivity, gate- and drain-lag transients, and restricted microwave power output. The research activity that is directed toward understanding and eliminating these effects parallels that of the GaAs-based technology, where previously significant attention was directed toward the minimization of trap effects [2].

In AlGaN/GaN HEMTs, the parasitic charge moving in and out of the traps on the surface and/or in the bulk of the heterostructure affects the density of the two dimensional electron gas (2DEG) in the channel, causing effects such as current collapse, and transconductance frequency dispersion. The characteristic time of the recharging process in GaN ranges between nanoseconds and seconds. As a result, the trapping effects can limit device performance even at relatively low frequencies. In addition, the thermally activated traps contribute significantly to the device low-frequency noise. Understanding the origin of the traps in GaN-based transistors, their location, and the physical mechanisms involved in the trapping is important for the optimization of device performance.

Currently, the trapping processes in GaN are not completely understood, in spite of the considerable research effort that has been directed toward identification and elimination of the traps. The majority of these studies provide only qualitative and often contradicting explanations of the trapping phenomena. This inconsistency existing in the field is largely related to the diversity of the trapping effects in GaN and its varying material quality. GaN contains high densities of defects and dislocations formed during the growth due to the large difference in lattice constants and in thermal expansion coefficients of the substrate and the epilayers. The defects and dislocations can potentially act as the charge carrier traps creating localized levels inside the bandgap. In addition, it is believed that the surface of the material contains a large density ($>10^{13}$ cm^{-2}) of donor-like states [3]. While the majority of the trapping effects result in similar degradation of the transistor characteristics at high frequencies, the dominating trapping mechanisms could vary in devices grown by different methods or subjected to different processing procedures. It is essential; therefore, that any characterization method differentiates between various trapping centers.

Terminology

It is important to note that the terminology being used has sometimes been inconsistent. The use of the terms as gate lag, drain lag, pulsed I-V, transconductance and output resistance dispersion, power drift, and power slump are generally used with little ambiguity in the literatures. Sometimes, current collapse is defined based on its origins in the GaAs technology. However, it is not uncommon to find the term "current collapse" applied to any measured reduction in drain current when, in fact, one of the other trap-related phenomena is being observed. Furthermore, the differences between the pulsed and dc drain characteristics and the differences between the expected microwave power output (based on the dc characteristics) and the actual power output are referred to as various types of "dispersion" or "slump" [4].

A variety of trapping effects in AlGaN/GaN HEMTs have been observed, including transconductance frequency dispersion, current collapse of the direct current (dc) drain characteristics, gate- and drain-lag transients, and restricted microwave power output. Significant research activity has been directed toward understanding and eliminating these effects. This activity in many ways parallels that conducted during the development of the GaAs-based technology. Much of the knowledge obtained and techniques utilized for the GaAs case can be applied to the wide bandgap materials as well.

In principle, trapping centers can reside at the surface, in the AlGaN barrier layer, at the two-dimensional electron gas (2DEG) interface, or in the GaN buffer layer. While it is known that defects exist in the AlGaN layer, a correlation with compromised microwave performance has not been established. This holds true for states at the AlGaN/GaN interface as well, although their presence is expected to limit the 2DEG channel mobility. Although there are a variety of conflicting explanations for the observed trapping effects, the picture that seems to be emerging is that trapping at the surface and in the underlying buffer layers are primarily responsible for compromised microwave power performance. It should also be noted that the nitrides are characterized by a high concentration (typically 10^8 to 10^{10} cm^{-2}) of dislocations. A number of studies have shown that electrically active trapping centers can exist in the vicinity of these extended defects. However, there is little information to directly link specific traps and trap-related phenomena with dislocations. Consequently, while some of the trapping phenomena may eventually be shown to result from defects localized at dislocations, it is not currently possible to distinguish these from traps located elsewhere in the material.

Buffer Trapping- Current Collapse

Current collapse in a nitride-based HFET is shown in Fig. 1, for characteristics taken both before i) and after ii) the application of a large drain bias. The drain current could be recovered by illumination with light either corresponding to the GaN bandgap or near 600 nm, the latter being associated with an unknown trap. Following earlier work done in the AlGaAs/GaAs system, the collapse was assigned to hot carrier trapping in the AlGaN. Current collapse is evident in comparing the I–V characteristics shown in Fig. 2(a), with (solid line) and without (dotted line) light illumination. At elevated temperatures (up to 155 C), the drain current exhibited little or no collapse, consistent with thermal emission from the deep traps, while the time dependence of the drain-current recovery reflected a multicomponent response, suggesting the involvement of multiple traps in the collapse. Under illumination, the qualitative wavelength dependence of the drain current recovery, shown in Fig. 2(b), suggested a broad, trap related absorption below the GaN bandgap. These results were interpreted in terms of deep traps in the high-resistivity (HR) organometallic vapor phase epitaxy (OMVPE) GaN buffer layer, which is grown under conditions that enhance trap formation in order to compensate the shallow donors and produce HR material. Further studies confirmed the location of the traps in the HR GaN buffer layer, as collapse was not observed in devices grown on conducting substrates: the traps in the structure were already filled by compensating shallow donors.

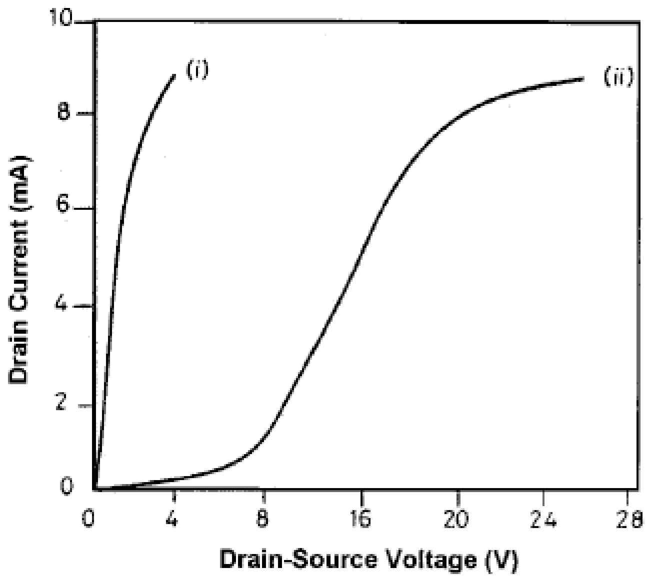


Fig. 1. Current collapse in an AlGaN/GaN HEMT [32]. Drain current as a function of drain–source voltage (with the gate floating) is shown i) before and ii) after the application of a 20-V drain–source bias.

By studying the wavelength dependence of the drain-current recovery in detail, it was possible to develop a method to provide spectroscopic signatures of the traps responsible for current collapse and to estimate the trap depth relative to the band edges. This was accomplished by measuring the fractional drain-current increase, above the collapsed level, induced by illumination with a measured amount of light. The wavelength dependence of this increase, normalized by the total number of incident photons, was shown to be proportional to the absorption spectrum associated with the photoionization process that released the carriers from the traps. This photoionization spectrum is a characteristic of a given trap and may be employed for defect identification. The spectrum obtained from a GaN MESFET at 300 K is shown in Fig. 3. Two broad absorptions were observed below the GaN bandgap, corresponding to the photoionization of carriers from two distinct traps, labeled Trap1 and Trap2. The fitted photoionization thresholds located these defects at approximately 1.8 and 2.85 eV below the conduction band, respectively. It is interesting that each of these absorptions was also found to match published spectra (see Fig. 3) of PPC centers in GaN indicating that these traps can induce both PPC and current collapse. The DX center in AlGaAs is also known to play this dual role. In the nitrides, a DX-like center associated with oxygen in AlGaN has recently been observed. This trap, like DX in AlGaAs, is effective only at low temperatures. However, in the nitrides, current collapse is observed at room temperature. It is, therefore, unlikely that collapse in nitride-based HFETs is due to a DX-like defect. This is supported by spectral measurements in the nitrides, which exhibit no increase in response at the AlGaN bandgap. Using a simple modeling approach, measurements of the dependence of the light-induced drain-current increase upon the total amount of incident light were fitted to enable the determination of area densities and photoionization cross-sections for each of the traps. In the GaN HFET, the densities for both traps were found to be mid-10^{11} /cm^2.

Other investigations suggest that the significant reduction in dc drain current t observed in GaN junction FETs (FETs) after application of high drain bias was a result of high field injection and subsequent trapping of electrons in the HR GaN buffer layer.

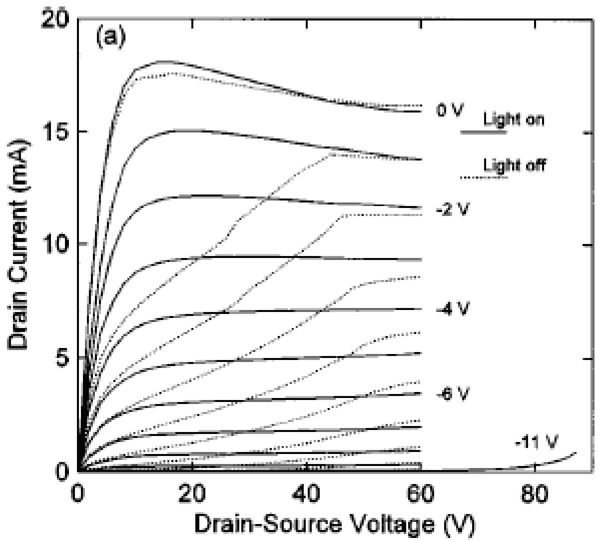
Photoionization measurements have also been carried out in AlGaN/GaN HEMT structures. The photoionization spectra were found to be similar to those of the GaN MESFET, exhibiting the two broad trap-related absorptions and a rapid increase at the GaN bandgap. No enhancement of the optically induced drain-current recovery was observed for photon energies at or above the AlGaN bandgap. This suggested that the same traps in the HR GaN buffer layer, which were responsible for current collapse in the MESFET, produced collapse in the HEMT as well. Lower pressures have been observed to correlate with more severe current collapse as well as a greater incorporation of carbon impurities into the layers. Photoionization spectra of these devices indicated a clear enhancement of Trap2 absorption at the lowest growth pressures. Both trap concentrations were found to increase at low growth pressures and the Trap2 concentration was seen to track the carbon concentration. The two were shown to be proportional, thus, suggesting that Trap2 is a carbon-related deep defect in the HR GaN layer. While the concentration of Trap1 did not track the carbon in the same way, the increase in trap concentration at low growth pressures, where dislocations and grain boundary effects are expected to be greatest, suggested that Trap1 may be related to these defects. The current evidence would suggest that current collapse in nitride-based FETs grown by OMVPE is associated with traps in the HR GaN buffer layer related to carbon incorporation and to structural defects.

Buffer Trapping-Drain Lag

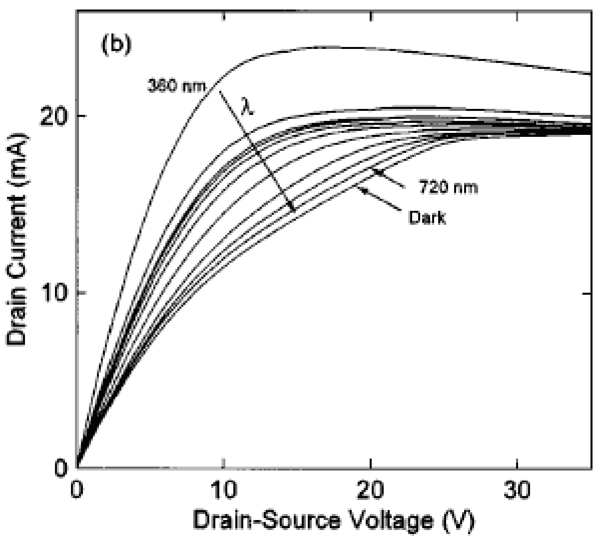
Recovery from current collapse by thermal emission of the trapped carriers has characteristic time dependence and the temporal response of the current collapse (i.e., reduced drain current) can be investigated with drain lag measurements. In addition to establishing this time dependence, drain lag measurements are also useful for quantifying this effect, since devices that exhibit minimal current collapse also exhibit minimal drain lag. The degree of drain lag is apparently related to the conductivity of the buffer layer. The deep levels responsible for producing the HR material are likely to be responsible for this trapping effect. Although drain lag is usually associated with buffer layer trapping, it was demonstrated that modifying the surface through the use of KOH exposure can result in changes to both gate and drain lag. Three traps were identified: 1) intermediate time constant traps (10 s), which were attributed to deep levels in the AlGaN; 2) fast traps (1 s), attributed to the surface; and 3) slow traps (100 s), which were associated with the channel. Further work is needed to clarify the effect that surface treatment has on drain lag.

Surface Trapping in GaN FETs

It is widely acknowledged that surface states or surface charge can have a pronounced effect on the microwave performance of HEMTs. As in the GaAs case, surface trapping can generally be identified through gate lag measurements. The association between gate lag and surface trapping is generally established by correlating gate lag with changes made to the device surface through techniques such as chemical treatment or dielectric passivation.



(a)



(b)

Fig. 2. (a) Current collapse in a GaN MESFET, with (solid) and without (dotted) light illumination. (b) Dependence of drain-current recovery on illumination wavelength [33].

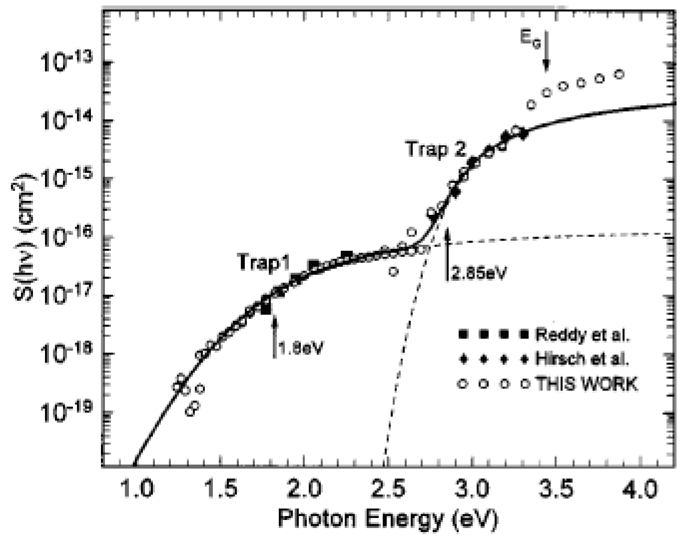


Fig. 3. Photoionization spectrum of a GaN MESFET. Two traps responsible for current collapse are observed. Spectra are similar to those observed in recent studies of PPC [35].

The most commonly encountered effect in the AlGaN/GaN HEMTs is gate lag. Gate lag is a delayed response of the drain current with respect to the gate voltage variation. It reflects recharging of the trapping centers as a result of variation of the gate potential. Charge temporally trapped in the vicinity of the transistor channel can reduce the drain current level by as much as 90%. In general, the trapping centers can be located on the device surface, in the AlGaN barrier, or in the GaN buffer. Because of a strong correlation of the effect with the semiconductor surface treatment, it was concluded that at least some trapping centers are located on the surface. It is believed that the AlGaN surface contains a large density of ionized donor states. The gate lag therefore has been associated with the ionized donor states located on the surface between gate and drain electrodes. The temporal character of charge emission from these traps is typically a stretched exponent with a characteristic time in the range of seconds. Practically no quantitative investigation of these trapping centers exists because of difficulties of the analysis of the stretched exponent dynamics. The presence of the trapped charge on the surface was confirmed by scanning Kelvin probe microscopy. The measurements showed that electrons migrate up to 0.5–1 μm along the surface away from the gate contact.

The surface states, however, are not the only source of the gate lag. The trapping centers in the barrier or in the buffer also affect the density of the 2DEG. The barrier trapping occurs due to charge tunneling from the gate into the semiconductor. The tunneling is assisted by a strong transverse electric field across the gate-to-channel barrier layer. The field also enhances the charge emission from the barrier traps. The field effects, therefore, are particularly important for the barrier traps and they must be taken into account during the characterization. The characteristic times of the field-assisted emission may vary from hundreds of nanosecond to milliseconds. Traps located in the buffer are usually associated with current collapse and drain lag. The transient effects related to these traps however appear in the gate lag measurements. The bulk traps were found to be sensitive to illumination and the information about the energetic location of the trapping levels was obtained from the photoionization spectroscopy. The spectrum revealed two broad absorptions corresponding to the traps in the middle of the GaN bandgap.

The non-exponential character of the trapped charge emission complicates quantitative characterization of the defects. Models of broad spectrum of trapping states have therefore been proposed to explain this behavior. On the other hand, DLTS studies of the defects in GaN and AlGaN Schottky diodes, which are solely sensitive to the trapping centers in the bulk, show distinctive spectral signatures. It implies that the trapping centers are characterized by localized levels within the bandgap. Most commonly observed are the deep levels with activation energies 0.18–0.25, 0.4, and 0.6 eV. A few studies showed similar DLTS peaks in the HEMT geometries confirming the localized nature of the observed traps. Spectral broadening can occur due to large densities of the defect states. The wavefunctions of the trapped electrons in this case overlap causing electron delocalization and the formation of a mini-band. The nonexponential character can also be caused by a non-uniform electric field distribution in the sample, emission from several different trapping centers, and phonon coupling.

Since gate lag is a delayed response of the drain current with respect to the gate voltage variation, it may be possible to induce this mechanism. Consider a system of equivalent localized trapping centers in the vicinity of the gate contact, with the ground level of trap within the bandgap. The potential at the gate electrode defines the position of the trap levels with respect to the Fermi level and therefore, its variation causes changes in the occupation factor of the trapping center. An electron can be captured on the trap from the conduction band or from the gate electrode. This is the basis of building the gate lag mechanism. The process of electrons capture by traps is important for the improvement of device characteristics. The possible mechanism by which the electrons migrate from the gate electrode to the traps is that of direct tunneling. The high electric field assists the tunneling process and results in the large number of the trapped electrons in the vicinity of the gate. The characteristic time of the process seems to be independent of the applied field.

In summary, the major origin of gate lag is related to electron trapping by the states located on the semiconductor surface and in the transistor barrier. Under the influence of the electric field, electrons tunnel through the gate contact barrier into the semiconductor. The electrons are captured by the traps in the vicinity of the gate edge, causing a partial depletion of the 2DEG in the transistor channel. Surface trapping has been shown to be minimized through the use of dielectric passivation. However, the dielectric passivation introduces its own reliability problems which limit its long term stability.

An area of particular concern is the limiting effect of electronic traps on microwave power performance. Traps influence power performance through the formation of quasi-static charge distributions, most notably on the wafer surface or in the buffer layers underlying the active channel. This parasitic charge acts to restrict the drain-current and voltage excursions, thereby limiting the high-frequency power output [2, 3, 4, 5, 6, 7, and 8].

Trap Cross Sections, Energy Levels and the Measurement Methods

Due to the critical role of traps in GaN-based devices, it is very important to recognize the nature of traps in these material systems. Thus, it is important to investigate traps in

$Al_xGa_{1-x}N/GaN$ heterostructures with different available techniques in order to extract characteristics of the traps, and understand their nature.

One of the most important characteristics of traps is the trap cross section. The values of the trap cross section obtained from the Fourier transform current deep level transient spectroscopy (DLTS) were on the order of 10^{-15} cm^2 for the traps with the energy of about 0.2 eV, 0.35 eV and 0.85 eV. Small values of the effective capture cross-section can be an indication that thee traps are located not in 2D gas but in the barrier layer. From the temperature dependence of the comer frequency, the activation energy could be extracted and obtained E~-0.35 eV. The summary is given in table 1.

Table 1. Trap activation energy and cross-section in AlGaN/GaN

Relaxation τ (sec)	Activation Energy E_a (eV)	Cross-section σ (cm^2)	Comments	Reference
5.2×10^{-3}	0.56	2.2×10^{-16}	Photoconductivity; sapphire substrate	[7]
7.0×10^{-3}	0.30	1.5×10^{-15}		
7.4×10^{-3}	0.21	4.9×10^{-15}		
-	0.21	4×10^{-14}	DLTS of n-GaN	[2]
-	0.45	7×10^{-13}		
-	0.29	-	DLTS of GaN HFET	[5]
-	0.85	7×10^{-15}		
-	0.42	-	Noise study	[12]
	0.35	-	Noise study	[14]

It is known that oxygen is a common contaminant in AlGaN, which is at least partially responsible for the background n-type conductivity. For Al content x>0.3 a DX center is formed which acts as an effective electron trap. The concentration of oxygen impurities in AlGaN epilayers can be very high up to $10^{19}cm^{-3}$, which is consistent with the noise spectroscopy data. Another possibility is that Si donors become DX centers for x>0.22. The activation energy of DX centers may change with the A1 content in the barrier, which would explain the different trap energies extracted for different devices. Charged dislocation lines may also contribute to the carrier density fluctuation noise [9].

Photoionization spectroscopy is an effective tool for probing the traps producing current collapse in HEMT devices. In particular, light illumination studies can provide a measure of the photoionization cross sections and the areal concentrations of the traps involved when an appropriate model of the trap photoionization process is available. The model assumes that current collapse occurs at high drain bias when hot 2DEG carriers are injected into the HR GaN layer, where they are trapped at deep defects, and that the drain current increase due to photoionization of the trapped carriers is proportional to the increase in the sheet charge of the 2DEG. While application of the model to experimental data is straightforward for a single trap species, for two or more traps the analysis requires minor modification. In order to account, for example, for the observed behavior of light illumination measurements where two traps are photoionized simultaneously, transitions from the higher-lying trap to the deepest trap (emptied by photoionization) can play an important role. This occurs when the photoionization rate out of the shallower trap is less than or comparable to the shallow-to-deep trap transition rate. Using photoionization spectroscopy together with fitting procedure gives the fitted area trap concentrations and photoionization cross sections.

The photoionization cross sections, ~10 ^{18}cm^2 for Trap 1 and ~ mid- 10^{16} cm^2 calculated for Trap 2, are typical for deep defects [10].

Table 2. Trap concentrations and photoionization cross sections for two traps responsible for current collapse.

Device	HR-GaN growth pressure (Torr)	n_s(10^{12}/cm^2) (Hall effect)	$n_{1,0}$ (10^{12}/cm^2)	$n_{2,0}$ (10^{12}/cm^2)	σ_1(633 nm) 10^{-18} cm^2	σ_2 (400 nm) 10^{-16} cm^2
1	65	9.3	1.37	1.74	0.2	4
2	150	12.1	0.74	0.26	1.5	6
3	200	11.5	0.96	0.45	1.1	6
4	300	12.2	0.61	0.55	3.5	8

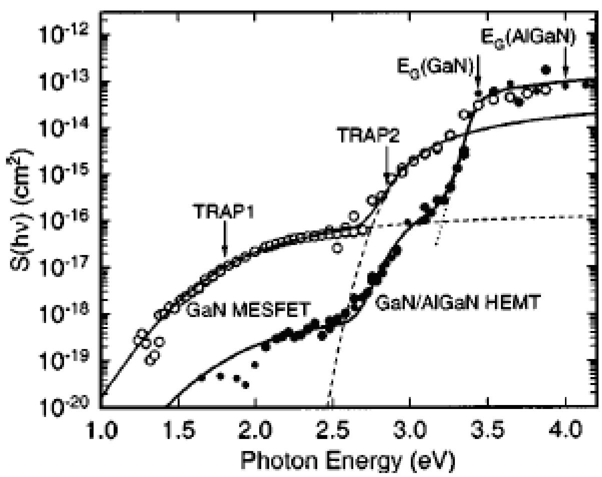


Figure 4. Photoionization spectra of a GaN MESFET and AlGaN/GaN HEMT structure.

Methods to Determine Levels in GaN-based Devices

The study of electrically active defects in highly compensated semiconductors where the density of trapping center is comparable to or greater than the net ionized dopant concentration is challenging because the space charge within a depletion region becomes a strong function of deep level occupancy. Deep-level transient spectroscopy (DLTS) is a powerful technique to detect traps and is widely used to determine trap parameters with high sensitivity. A frequency of 1 MHz is usually employed as the frequency to measure the capacitance of diodes. However, the capacitance must be measured with lower frequencies for samples with higher series resistance. DLTS and capacitance (*C*)-voltage (*V*) measurements could be used to reveal electron trap concentration as well [13].

Deep-level transient spectroscopy has been used to characterize electronic defects in *n*-type GaN grown by reactive molecular-beam epitaxy. Five deep-level electronic defects were observed, with activation energies *E*1=0.23460.006, *E*2=0.57860.006, *E*3=0.65760.031, *E*4=0.96160.026, and *E*550.24060.012 eV. Among these, the levels labeled *E*1 , *E*2 , and *E*3 are interpreted as corresponding to deep levels of *n*-GaN grown by both hydride vapor-phase epitaxy and metal organic chemical vapor deposition [11].

Deep level defects in Mg-doped, *p*-type GaN were characterized by deep level transient Spectroscopy (DLTS) and photoemission capacitance transient spectroscopy (ODLTS). The measurements were conducted on n^+-p junction diodes grown by metalorganic chemical vapor deposition. DLTS revealed discrete deep levels in the lower half of the band gap with activation energies for hole emission of 0.21, 0.39, and 0.41 eV. While DLTS is able to detect deep levels only in the proximity of the valance band edge in *p*-type, wide band-gap semiconductors, ODLTS enables detection of deep levels throughout the band gap of GaN. The ODLTS spectrum of Mg-doped, *p*-type GaN is dominated by a deep level with optical threshold energy for photoionization of 1.8 eV. This deep level, which appears to be energetically located near midgap is present in the highest concentration (2.4×10^{15} cm^{-3}) among the deep levels detected in GaN material. None of the detected deep levels is present in sufficient concentration to significantly compensate the shallow acceptor dopant in Mg-doped, *p*-type GaN. Deep levels located deeper in the band gap of *p*-type GaN than the Mg acceptors are also candidates for hole traps. Deep levels have previously been investigated by deep level transient spectroscopy (DLTS) for undoped and Si-doped, *n*-type films and with photoemission capacitance transient spectroscopy (ODLTS) for Si-doped, *n*-type GaN but not for *p*-type material [12].

Carbon incorporation in GaN has received substantial interest for p-type doping and more recently to form semi-insulating nitride layers for use in high electron mobility transistors. The mechanism for achieving semi-insulation is thought to be via self-compensation by the introduction of both shallow carbon acceptors and donors, and the possible introduction of deep states. The identification and nature of C-related bandgap states in GaN is complicated not just by the amphoteric nature of carbon, but also by the probable formation of defect-carbon complexes that may generate a wide range of deep levels in the GaN bandgap. Hence, deep level optical spectroscopy (DLOS) and related techniques are used to detect and quantify carbon-related shallow and deep traps responsible for semi-insulating behavior. DLOS is well-suited to this problem, not only because of its ability to detect traps throughout the bandgap, as opposed to DLTS which is limited by thermal emission, but also because DLOS can naturally probe compensating states that are close to the minority carrier band edge. To characterize GaN with an intentionally wide range of carbon incorporation, studies were made on both atmospheric pressure (AP) and low pressure (LP) MOCVD grown GaN films. Secondary Ion Mass Spectroscopy (SIMS) was used to confirm that LP MOCVD GaN layers incorporated a significantly higher carbon concentration of $\sim 4 \times 10^{17} cm^{-3}$ compared to a carbon concentration of $\sim 3 \times 10^{16}$ cm^{-3} for AP MOCVD GaN layers. Both DLOS and conventional DLTS measurements were made on a series of LP and AP MOCVD GaN layers to quantify traps throughout the entire bandgap by using Ni Schottky junctions formed on the epilayers [14]. Deep-level transient spectroscopy (DLTS) is also used to investigate the electron trap defects introduced in n-GaN during the fabrication of Pt Schottky contacts by electro-deposition, electron beam deposition and sputter deposition [15].

Since self-heating effects limit the performance of high-power AlGaN/GaN HFETs, knowledge of the temperature in the active area of AlGaN/GaN HFETs is essential for optimizing device design, performance and reliability; however, direct measurement of this temperature is not achieved. Infrared techniques often employed to measure the temperature of an active device require extensive calibration and have limited spatial resolution when compared with the only micron-size source-drain opening by micro-Raman spectroscopy allowing temperature measurements with 1 micrometer spatial resolution, important for local device geometries in the micron/sub-micron dimension range. This novel approach allows fast temperature measurements with minimal influence on device performance [16, 17].

A lighted capacitance–voltage (LCV) method for spatially profiling defect levels in wide band gap, highly compensated materials is used as well. Combined with deep level optical spectroscopy, the optical nature of the LCV profiling technique enables the quantitative study of lower bounds of concentrations for multiple deep and midgap levels. Unlike many other approaches to measuring large deep level concentrations in resistive semiconductors, this LCV method requires no constant-capacitance feedback circuit and is applicable to wide band gap materials such as GaN and SiC [24].

There are also other techniques and methods to determine different levels in wide band semiconductors.

Charge Control

There are two important issues that govern the AlGaN/GaN high electron mobility transistors (HEMTs) which are significantly different from HEMTs made from structures such as AlGaAs/GaAs or InAlAs/InGaAs. The first has to do with the very strong piezoelectric effect present due to the lattice mismatch between AlGaN and GaN. It is known that group III nitrides have large piezoelectric constants along the (0001) direction. When (0001)-oriented thin AlGaN layers are grown pseudomorphically on a thick GaN, the biaxial strain induces a piezoelectric field in the material. As a result, there is a strong interface charge at the HEMT interface. The second effect has to do with interface roughness. Although this effect is present in other HEMT structures as well, the larger band discontinuity combined with larger effective mass in the channel makes interface roughness much more important in controlling the channel mobility. Additionally, the combination of interface roughness and piezoelectric effect can cause the charges at the interface to be distributed nonuniformly.

In fact, a unique feature of AlGaN/GaN material system is the high sheet carrier concentration (in the order of 1×10^{13} cm), which can be achieved in the channel not only due to the large bandgap discontinuity at the interface, but also due to the pizoelectric and spontaneous polarization effects without intentionally doping the barrier layer. Theoretical and experimental studies carried out by many researchers showed the effect of both spontaneous and piezoelectric polarizations on the carrier distribution at the heterointerface, and the importance of proper inclusion of these effects in the analysis of III nitride structures.

In the area of device modeling, several theoretical models have been reported in the literature. One group of these models solves Poisson's equation coupled with Schrodinger's wave equation self-consistently using trial wave functions [18]. However, the treatment of the 2DEG was carried out in a similar way like that in AIGaAs/GaAs HEMTs, and the obtained results reflected only the difference in material systems of the two devices. Another group of models gives simple analytical formula for the sheet carrier density n_s versus the Al mole fraction x, for normally undoped HEMT structures including piezoelectric polarization effect. This formula was further modified to include the effect of both spontaneous and piezoelectric polarizations and doping of the barrier layer [19, 20]. In another attempt, an analytical expression for the Fermi-level versus ns and interpolation formulae for calculation of the polarization sheet charge density are given. Non-linear formulae for the polarization effects were incorporated into a quasi-2D model presented in, instead of the linear interpolations used before [21].

A simplified numerical model to characterize the charge control in AlGaN/GaN HEMTs could be given by using the basic phenomena of spontaneous and piezoelectric polarization as well as the ones used for estimation of their values. It is said that the model could explain the effect of spontaneous and piezoelectric polarization, the 3 -D free carriers, and the neutralized donors in the doped layer in the sheet charge calculations [1].

Numerical formulas have been developed to study the charge control and transport of AlGaN/GaN-based HEMT device. The charge control model is based on a self consistent solution of the Poisson equation and Schrodinger equation. Piezoelectric effect due to strain is modeled by including a polarization field. In examining transport in the two-dimensional channel, much of present understanding of transport in semiconductor devices depends upon the use of Born approximation and the independence of various scattering mechanisms. Scattering mechanisms such as ionized impurity scattering, interface roughness scattering, alloy scattering, etc. are handled within the Born approximation and are assumed to act independently. In many problems of interest, it is known that Born approximation is not valid but it is still used because of the complexity of the problem. Examples include transport in metal–oxide–semiconductor field effect transistors (MOSFETs) at low temperature when a significant fraction of carriers are in the localized bandtail states, transport in clustered alloys etc.

For the AlGaN/GaN system, some simulations show that there is considerable localization of low lying electronic states. While Born approximation becomes invalid under these conditions, the Kubo formula is used to study transport. The breakdown of Born approximation reflects itself in mobility increasing with temperature—a signature of hopping conductivity. At high temperatures, the Kubo formula and Born approximation give similar results. The temperature at which the two formalisms become equally valid depends on the interface roughness parameters. It is claimed that a very high sheet charge density can be produced due to the strong piezoelectric effect at the interface. The sheet charge density increases with increase in Al fraction in the barrier. The increase is primarily due to the higher piezoelectric charge. Solving the three-dimensional Schrodinger equation for the HEMT in presence of interface roughness shows that even a small amount of interface roughness causes localization of low lying electron levels. To study transport in such a system, the Kubo formula is used. The results of this model show that for strong interface roughness the mobility around 77 K is essentially independent of temperature and even shows a region where it increases with temperature. The mobility in a HEMT with a rough interface degrades with increased Al composition in the barrier [22].

It should be noted that some investigations focus on showing the implementation of the deep-level effects in the device models. Then it is claimed that the charge control model provides a good physical understanding of HEMT operation and is easily applied to a wide variety of HEMT structures including pHEMT and multichannel HEMT. However, the conventional charge-control models are inadequate in characterizing the DX centers and substrate related phenomena. The new self-consistent charge-control models incorporating deep level effects could take into account DX centers, substrate trapping and strain in GaN HFETs. The conventional charge-control models are also insufficient to describe HEMT's operation in a depletion-mode and near pinch-off [24].

Long Term Degradation and Physics of Failure

High electron mobility transistors fabricated from nitride semiconductors utilizing the AlGaN/GaN heterojunction demonstrate excellent performance in RF range. However, the nitride devices demonstrate reliability problems where the dc current and RF output power continually decrease as a function of time. One of the reliability problems is related to the conduction characteristics of the gate electrode and an electron tunneling mechanism where electrons leak from the gate to the surface of the semiconductor. Although the degree of performance degradation varies with the design, processing steps, and device manufacturer, all high voltage AlGaN/GaN transistors are affected and the problem is more severe as operating frequency is increased. However, the more detailed study should consider trap generations, trapping behaviors (regarding long-term and temporary recovery), and correlation between damage and trap density. The degradation mechanism should include issues such as piezoelectric effects, tensile strain, and electron trapping, defect formation, Aimed to predict electrical behavior of the device (Current Collapse, Power soak, DC and RF Degradation).

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