Failure Modes and Effects Criticality Analysis (FMECA) of AlGaN/GaN Based Microwave Device Degradation Mechanisms

by

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Abstract

This paper reviews the main degradation mechanisms of GaN-based HEMTs (High Electron Mobility Transistors) based on surfaces, interfaces, substrate and technology issues. Failure Mode and Effects Analysis is proposed as a powerful design assurance technique to identify and minimize potential problems in a process design. The product of an FMECA is a table of information which summarizes the analysis of all possible failure modes.

Introduction

The properties of Ill-V nitride heterostructures have found a wide range of applications ranging from microwave and millimeter products to photonics. Applications include the blue-green light emitting diodes and lasers, high power amplifiers, high temperature electronics. The reliability of HFETs have reached a level where rapid system insertion is possible. Since the bandgap is wide (approximately 3.43 eV), the high temperature applications may be realized. Also this wide bandgap allows very high electric breakdown (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 is in the range of 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.

One area of active research deals with the reduction of trap effects in GaN-based devices. The observation of electron traps, especially at 0.5-0.65 eV as identified by DLTS results in the threshold voltage varying with light and temperature. Because of these traps, the threshold voltage can vary excessively with temperature after an initial high temperature accelerated life test. The research activity that is directed toward understanding and eliminating these effects parallels that of the GaAs-based technology, where initial attention and research efforts were directed toward the minimization of trap effects [2].

In AlGaN/GaN HEMTs, the presence of surface states especially between the AlGaN and the GaN, as well as in the vicinity of the gate- source access regions and the passivation layers will affect the two dimensional electron density. The effect of surface states on HFET behavior depends on many factors such as density, activation energy and temperature. The total effect of surface states is the lowering of the field in the gate-drain region, since negative charge is captured. The presence of deep levels associated with surface states causes many phenomena such as gate lag and trans-conductance dispersion.

We know that gate-lag is due to the distortion in the drain current transient signal. Trans-conductance on the other hand is due to a decrease of g_m with increasing frequency and is probably affected by both the source and drain parasitic resistances. These resistances are also known to be a function of the parasitic charge. Both trans-conductance dispersion and gate lag seem to occur on the same device and we have found it to be affected by the surface state density. Therefore, the higher the net trap density, the greater will be the phenomena of gate lag and frequency dispersion. In addition, we can obtain a thermally induced change in g_m, in both biased and unbiased HFETs, which does affect the gate to drain breakdown voltage. The channel passivation also critically affects gate lag as well as does selective ion etching of the channel region. De- passivation can produce a recovery in both g_m characteristics as well as gate to drain breakdown voltage. We can also report that a reduction in the surface state density at the Si_3N_4-GaN interface can also decrease the breakdown voltage and result in device catastrophic failure.

The available data, as well as our experiments indicates that the effect of surface and interface state is not well understood. The AlGaN/GaN HFETs have been by now well established for power applications as well as for low noise applications, and have replaced many of the conventional AlGaAs/GaAs HFETs. However, these devices are still affected by a variety of trapping and materials related reliability problems.

The AlGaN/GaN HFET degradation mechanisms fall into two main categories. The first type are the ones detected in AlGaAs/GaAs HEMTs with the main difference being due to the unique polarization layer of AlGaN. The second one consists of degradation mechanisms mainly due to trapping mechanisms on AlGaN surfaces, interfaces and buffer layers. The second category also includes traps generated at the buffer-substrate interface and also due to the strain from the lattice mismatch conditions. Other secondary degradation type mechanisms such as I-V collapse and photoconductivity effects appear to be due to device processing technologies. There is much inconsistency in the data reported for AlGaN/GaN HFETs and in general shows that the physics of electron traps is not well understood. However, the strain effects at the drain edge appears to generate a large density of dislocations which by themselves will create deep level traps. The dislocation density initially approximated from strain relaxation is of the order of 10^{10} cm^{-2}. These dislocations result in deep levels which can be considered to be donor-like states in the bandgap. The dislocation -created donor like states do result in localized levels within the band gap and do agree with varies reported density of donor like states. However, surface roughness and surface scattering will also result in near surface states (shallow donor states). Indeed, references 3 and 4 do report that the surface of the material does contain a large density of donor-like states [3,4].

Buffer Trapping- Current Collapse

Current collapse is usually associated with deep traps within the buffer layer. These deep traps can alter the electrical properties of HFETs leading to current collapse as well as persistent photoconductivity. Since current collapse is observed at elevated temperatures, then we can attribute this mechanism to thermal emission from and to these deep level traps. The thermal emission from these deep traps can be measured at various bias levels and has been measured to have activation energies from 0.40-0.47 eV. In addition, illumination effects have clearly shown that current collapse is due to the existence of multiple traps, and not due to one unique trap. The main question which remains is whether these traps only affect performance of devices and not reliability.

However, the result of low temperature storage test does suggest that there are additional changes in the upper buffer interfaces which occurs at elevated temperatures. These changes may be explained by additional traps and an increase in the magnitude of the kink effect. Similar effects may also be produced by ohmic contact degradation and related interdiffusion effects.

The long term transients which are present due to trapping of electrons by ionized donors is shown in Figure 1. A transient present in the drain current response of a normal HFET is a clear signature of buffer layer trapping.

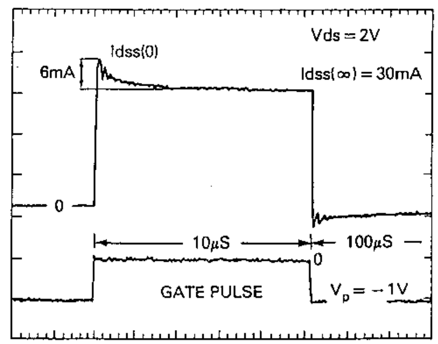

Figure 1. Shown is a drain current transient effect due to an incident gate pulse.

The drain current transient shown in Figure 1 plays a significant role in characterizing the traps. By studying the wavelength dependence of the drain-current while elevated temperature recovery takes place, we can determine the position and density of the trap, as well as its position near the band gap edge. This technique was initially developed by Binari et al (ref 7) as has shown that such traps are DX like in both position and trap density. Indeed DX centers in AlGaAs showed multiple energies, and do show a band gap edge dependence. Since the dependence on Al mole fraction was not observed for AlGaN, we may conclude that the traps measured in AlGaN are not DX like in energy position and trap density. Current collapse in nitride based HFETs are therefore not due to DX like defects. We may conclude that current collapse is due to a broad number of electron traps, with the origin being the buffer layer. However, additional experiments are necessary in order to fully understand these traps.

The buffer layer does have interfacial roughness as well as strain energy problems and hence may be entirely due to process and material growth issues. Photoionization measurements have also been carried out in AlGaN/GaN and the results do show a wavelength dependence initially reported in reference 7.

Buffer Trapping-Surface Trapping and Gate Sinking

The effect of inter-diffusion, probably due to gate sinking, results in an increase in impurity scattering. Impurity scattering, can result in a degradation in channel mobility. The new channel mobility from our measurements varies inversely with impurity ion concentration. The deep level impurity may be determined by considering the hydrogen-like nature of these impurities. Hence the decrease of electron mobility is due to an increase in impurity scattering given as:

$$\mu \propto \frac{1}{N_I} \quad \Rightarrow \quad \Delta\mu / \mu_0 \approx \frac{1}{1 + N_D / N_{imp}}$$

It is this decrease in channel mobility which results in current collapse, and a reduction in drain current. The recovery process from current collapse can only occur via thermal emission from the impurity traps. Hence, the increased impurity scattering results in a decrease in drain current which also decreases the threshold voltage. The decrease in drain current can be explained through a change in the donor layer impurity concentration. The donor layer density can decrease from simple trap compensation effects as shown in Figure 2, and we have concluded that such a change can result in current collapse.

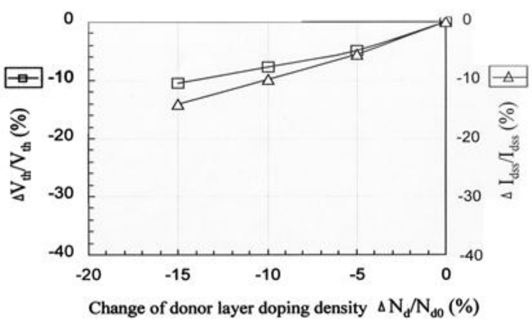

Figure 2. Donor compensation effects due to trapping effects results in a change in donor layer density.

We have concluded that current collapse is due entirely to donor compensation effects through near surface traps. Electron traps at 0.65 eV present after elevated temperature stresses do show a trap density dependence. The threshold density also shows light sensitivity at elevated temperatures. The large light sensitivity corresponds to the increase in trap density. The drain lag phenomena, being due to trapping effects may be used to study the recovery effects from these trapping mechanisms. One may establish a time dependence, a characteristic time constant as well as a wavelength dependence. The deep levels which we have measured to be present at 0.50-0.65 eV can be recovered at temperatures in excess of 200^0C. Drain lag has been attributed to the degree of impurity compensation of the high resistance buffer layer, and hence the conductivity of the buffer layer. We may categorize the traps according to the recovery time constant, with the slow traps (greater than 100 s) being due to the electron channel, and the fast traps being due to surface defects. The intermediate traps, of the order of 10-20 s, are attributed to AlGaN defects resulting in deep trapping centers. The fast trap time constant may be changed by surface etching however. Since native oxides show amphoteric behavior one may use either acidic or alkaline etchants. All etching processes are affected by a large number of factors, and it is not surprising that we can get a variation of time constants for the fast surface traps.

Surface Trapping in GaN FETs

The surface quality of GaN or AlGaN before metal deposition is strongly affected by etching processes. Since the morphology is fixed during metal deposition, the presence of surface traps will affect metallization performance. Surface roughness will also play a major role. The critical role of surface trapping on long term reliability however, may only be speculated since the evolution of surface traps as a function of time and temperature have not been determined.

Electron traps can limit performance, but their effect on long term reliability has not been directly determined. We can only project that enhanced diffusion effects may be accelerated as well as a propensity for electromigration to occur. The electron traps will limit performance and through threshold current degradation will limit microwave performance.

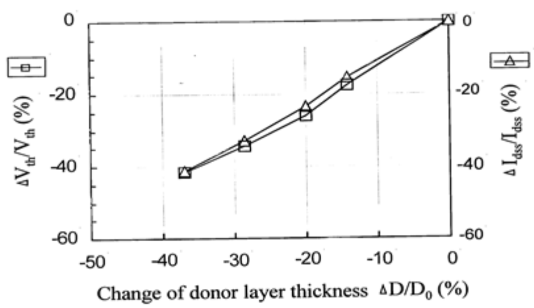

Figure 3. A decrease in saturation current which may result from gate degradation effects is shown in the above figure.

Electron traps will decrease the effective donor density concentration which may be modeled as an equivalent donor layer thickness. Figure 3, shows a shift in threshold voltage and its dependence on donor layer thickness. The same decrease in donor layer thickness may occur via gate interdiffusion, which is a time dependent failure mechanism. Since there is a decrease in the effective donor layer thickness, an excess of parasitic charge exists which limits microwave power output. The role of parasitic charge in limiting high frequency performance has been previously reported [2, 3, 4, 5, 6, 7, and 8].

Charge Control Modeling

AlGaN/GaN high electron mobility transistors (HEMTs) are significantly different from HEMTs made from structures such as AlGaAs/GaAs or InAlAs/InGaAs. The lattice mismatch between the AlGaN and GaN produces a very strong piezoelectric charge, and hence exhibits a classical ferroelectric phenomena. The growth of the AlGaN layers are accomplished pseudomorphically and results in a large lattice mismatch which produces a biaxial strain and hence a large piezoelectric field. 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 non-uniformly. The charge control calculations must include piezoelectric field as well as interface scattering.

Reliability models of the physics of failure starts by solving Poisson's equation coupled with Schrodinger's wave equation self-consistently (same results as AIGaAs/GaAs HEMTs). Our approach is to start with simple analytical formula for the sheet carrier density versus the Al mole fraction x (for normally undoped HEMT structures including piezoelectric polarization effect). Additionally, the subsequent step is the model modification to include the effect of both spontaneous and piezoelectric polarizations and doping of the barrier layer.
Our model is based on a derived analytical expression for the Fermi-level versus n_s and interpolation formulae to calculate the polarization sheet charge density of AlGaN/GaN heterostructures. Overall we can proceed to derive non-linear formulae for the polarization effects incorporated into a quasi-2D model (instead of the linear interpolations used before). This approach results in degradation calculations and a ranking of such degradation as well as their criticality.

Physics of Failure and Criticality Analysis

In carrying out a criticality analysis, there are three approaches to charge control modeling. In (I), a simplified numerical model using the basic phenomena of spontaneous and piezoelectric polarization as well as the estimation of their values has been developed. The model explains the effect of spontaneous and piezoelectric polarization, the 3 -D free carriers, and the neutralized donors in the doped layer as part of the sheet charge calculations.

In Charge Control Model 2, the approach is based on a self consistent solution of the Poisson equation and Schrodinger equation. The piezoelectric effect due to strain is modeled by including a polarization field. The Born approximation and the independence of various scattering mechanisms by examining transport in the two-dimensional channel is included. All scattering mechanisms (such as ionized impurity scattering, interface roughness scattering, alloy scattering, etc.) are handled within the Born approximation. In charge control model/ 3, the Kubo formula is used to study transport. The breakdown of the Born approximation is reflected 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). In addition, a very high sheet charge density can be produced due to the strong piezoelectric effect at the interface. The results of these models can be inserted in a failure modes criticality analysis (FMECA) that is often used when multiple failure mechanisms are present.

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