GaN Microwave Transistors: How the Reliability Challenges Have Been Solved

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Microwave transistors based on GaN deliver outstanding performance because of basic material advantages of high breakdown voltage, high carrier density and good mobility. They now give unmatched lifetime and robustness, are space qualified, and are displacing traditional solid-state technologies in numerous applications. However, this performance did not come without a struggle. The primary problem areas which have impacted the performance and reliability of GaN microwave devices are identified, and the techniques discussed which have been used to control or mitigate their impact.

INTRODUCTION

Microwave transistors based on GaN can deliver outstanding performance because of basic material advantages of high breakdown voltage, high carrier density and good mobility. They now deliver unmatched lifetime and robustness, are space qualified, and are displacing traditional solid-state technologies in numerous applications[1]. However, this performance did not come without a struggle. The primary problem areas which have impacted the performance and reliability of GaN microwave devices are identified, and the techniques discussed which have been used to control or mitigate their impact. This paper highlights the control of current-collapse from surface and bulk traps, the suppression of high-temperature reverse-bias gate edge breakdown, the effect of doping of the buffer, and the impact of the epitaxial growth approach on the crucial parameter for reliability - thermal resistance.

Reliability Issues

The basic RF GaN HEMT is shown in Figure 1 with the primary reliability issues highlighted [2]. There are some basic differences from a traditional GaAs based device in particular it relies on a built-in polarization charge at the heterojunction between GaN and AlGaN to induce a 2D electron gas (2DEG) in the GaN region, so there is no requirement to use doping of the AlGaN barrier as a source of the free carriers. In addition, in the absence of large area GaN substrate wafers at viable cost, the epitaxial layers of Ga based alloy are normally grown on a heterogeneous substrate where the usual choice for RF applications is highly thermally conducting electrically semi-insulating SiC.

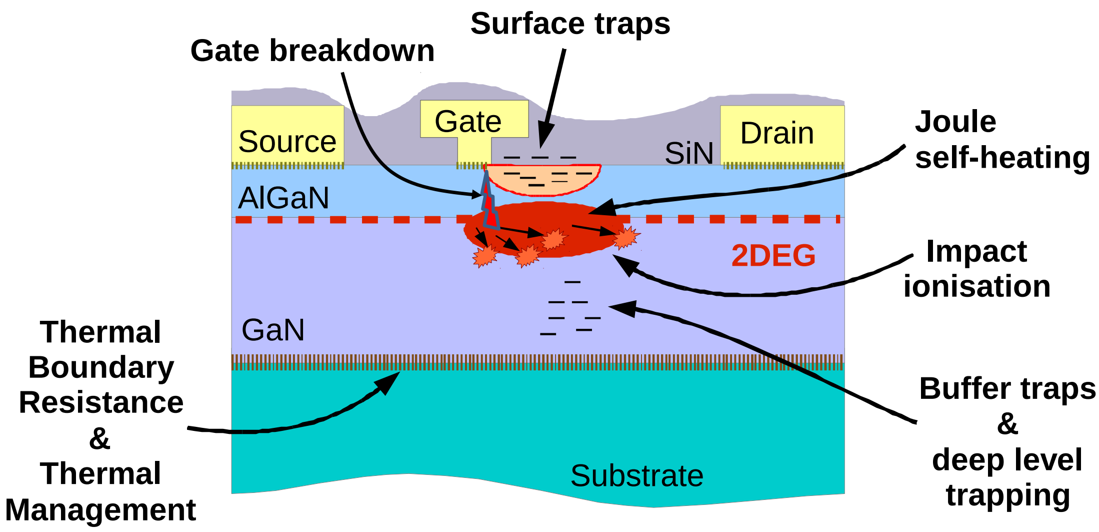

Fig. 1. Schematic diagram of the GaN HEMT showing the key regions which are vulnerable to trapping and degradation

The specific areas which cause reliability and GaN specific performance issues are highlighted in the figure. They include transient and long period charge trapping on the surface of the AlGaN barrier and within the GaN buffer region under the conducting 2DEG. Gate leakage in Schottky gated transistors has been a particular issue leading to wear-out and eventual failure. A specific issue that arises from the use of a non-lattice matched substrate such as Si or SiC is that there is a huge density of threading dislocations (typically between 10^8 and 10^{10} cm^{-2}). Surprisingly these defects have proved to be relatively benign electrically, but they do generate a thermal boundary resistance. Many of the damage mechanisms are thermally activated and linked to the availability of hot-electrons, so a key aspect is controlling self-heating and hence thermal resistance. Here we will discuss the solutions that have been adopted for each of these issues and which have led to the manufacturable technology which is available today.

Surface Trapping - Current-Collapse

When GaN HEMTs were first developed in the 1990s[3] the devices showed extreme surface sensitivity and bias history dependence which was soon identified as being largely the result of surface trapping[4]. It was found that the high lateral electric field at the point where the Schottky gate metal touched the AlGaN or GaN surface (the AlGaN barrier layer is often capped with a thin layer of GaN) allowed lateral electron transport into surface trapping states. Electron trapping on the surface resulted in a “virtual gate” which extended the physical gate towards the drain and reduced the electron density in the 2DEG below this trapped negative surface charge. The consequences for an RF device are severe, resulting in an increase in drain resistance, a knee walkout and consequently a DC-RF dispersion and a reduction in PAE[5]. This behaviour is frequently termed current-collapse. At first sight it might seem that the solution would be passivation of the surface and the removal of all active surface states. However it turns out that surface donor traps are inherent in GaN HEMTs and indeed are essential for the functioning of

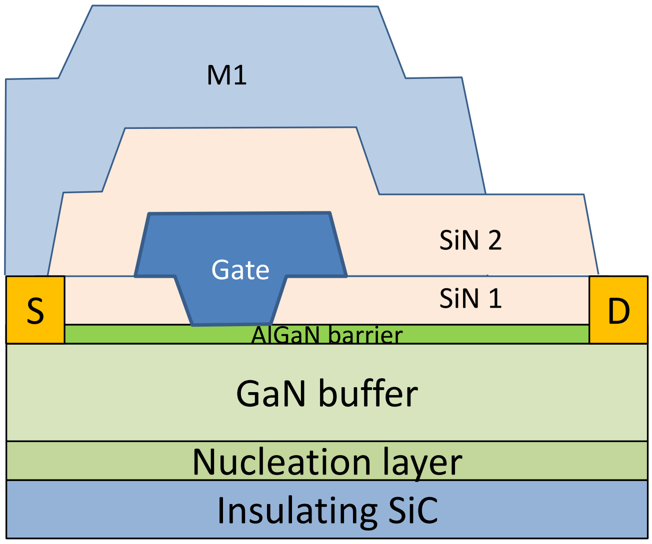

Fig. 2. Schematic cross-section of a field-plated RF HEMT.

the device, since positive charge stored in the surface donor states provides the matching charge to the 2DEG charge[6]. Removing the surface states would remove the 2DEG. So in GaN devices the objective of "passivation" of the surface is not to remove the surface traps, but instead to reduce the lateral conductivity across the surface between those traps. Devices without any surface deposited layer show extreme sensitivity to moisture and are highly unstable, however it has been found that many different encapsulating "passivants" can successfully reduce the current-collapse by excluding moisture without changing the essential surface charge. Most devices now use Si_3N_4 as the "passivant" [7] but it is far from being the only successful deposited layer.

It has been found that lateral electron transport between the surface traps occurs by a Poole-Frenkel process[8] which is strongly electric field dependent. So the key objective in designing the gate for minimum current-collapse is maintaining the surface electric field at the gate to (Al)GaN interface below the threshold for lateral conduction. This field is typically in the vicinity of 1-3MV/cm. The primary route by which this electric field control is accomplished is shaping the gate and through the use of field plates [9-11]. Figure 2 schematically shows the solution that has been widely adopted by manufacturers such as Triquint (now Qorvo) and UMS. The process flow involves deposition of the silicon nitride passivation, opening a sloped sidewall window down to the AlGaN surface, deposition of a Schottky gate metal, deposition of a second dielectric layer, and then deposition of a metal layer to form a source-connected field plate. This process flow has several key advantages which more than outweigh the possibility of plasma etch damage to the AlGaN surface. Firstly the passivation is deposited early in the process reducing the possibility of surface contamination, secondly the gate to AlGaN interface is sloped which reduces the electric field at the gate corner, the overhang on the gate forms a field plate which spreads the electric field once the drain voltage exceeds its pinch-off voltage, and the source field plate again spreads the fields at higher voltages. Equally importantly the source field plate reduces C_{GD} and improves RF gain.

Gate Degradation

A major reliability issue with GaN HEMTs is soft-breakdown of the gate. When stressed in the off-state with a high drain bias, the gate current displays a wear-out phenomenon similar to the time-dependent-dielectric-breakdown mechanism seen in silicon MOSFETs. Discrete soft-breakdown events occur, each resulting in a few microamps of leakage current from gate to channel, and each showing an electroluminescent spot signature [2, 12]. There is a gradual increase in current as increasing numbers of leakage paths appear leading to eventual failure. The time-to-failure is strongly bias dependent obeying Weibull statistics and occurring at longer timescale the lower the electric field[13]. Several mechanisms have been advanced including piezoelectric induced cracking [14] but now the belief is that there is a gradual build-up of defects within the barrier[13]. In addition it is found that there is an electrochemical degradation of the (Al)GaN surface at the gate corner driven by the availability of reactants at the surface[12, 15]. In practice it has been found that optimising the thickness of a thin GaN cap on the surface of the AlGaN layer and changing the surface cleaning can reduce the susceptibility of RF devices to gate leakage and deliver a sufficiently long working lifetime [16]. As is the case for current-collapse, a key part of managing the wear-out of the gate barrier is controlling the gate shape and using field plates to maintain the peak electric field below the onset of degradation.

The standard HEMT makes use of a Schottky gate for control of the channel conductivity, and this can be a source of problems at elevated temperatures. Initial devices made use of Schottky metals such as nickel which proved satisfactory at temperatures well below 300°C, however increasingly more refractory metals are now being employed which deliver excellent high temperature reliability[17].

Buffer Effects

Trapping in the GaN buffer is inherent in the standard single-heterojunction HEMT since it has to be doped with a deep-level trap to render it insulating and prevent parallel parasitic off-state leakage through the buffer between the source and drain[18]. Various choices of deep trap which pin the Fermi energy deep in the GaN bandgap have been tried, but it has been found that iron[19] delivers spectacular RF power and excellent leakage performance[20]. There are still some residual trapping issues but these are reproducible and manageable provided the Fe density is reasonably low in the vicinity of the 2DEG[21, 22]. For RF users it needs to be borne in mind that associated with the iron trap level is a small low frequency dispersion which manifests itself as a transconductance dispersion and low frequency noise around 10Hz at room temperature [23]. Iron as a doping solution works well for RF applications requiring drain voltages up to 100V, however for power switching applications where voltages of 600V are normal, carbon has become the dopant of choice despite resulting in considerable trapping issues[24].

Thermal Effects

The great advantage of GaN HEMTs is their huge power handling capability; however this of-necessity results in self-heating. Since the primary remaining failure mechanisms are largely driven by thermal effects [1], it is essential for reliability prediction to have an accurate measure of the channel temperature, which in practice can easily exceed 200°C in multifinger power devices. Traditional III-V techniques for temperature measurement such as electrical analysis and infra-red imaging have proved to be inadequate due to trapping issues and the poor lateral resolution and transparency of the substrate respectively.

The technique of choice for accurate device temperature measurement has become Raman spectroscopy[25]. Raman thermometry uses a focussed sub-bandgap laser to observe the excitation of phonon modes in the GaN layer which are temperature dependent, thus delivering a sensitive highly-local temperature probe with virtually no lattice heating. This technique when combined with thermal modelling delivers ~5°C temperature resolution with 0.5μm lateral resolution and 10ns time resolution[26, 27]. Direct measurement of the temperature of a GaN-on-SiC transistor has proven to be essential in establishing its thermal resistance – it is not sufficient to use literature values for thermal conductivity of each layer in the structure in a thermal model. This is because the thermal resistance of the nucleation layer between the GaN and the SiC is highly growth process dependent resulting in as much as a 30% change in the thermal resistance of the structure[28]. Further improvement in power handling over the incumbent solution of GaN-on-SiC are being investigated by using diamond as a growth substrate, although this clearly has both thermal mismatch and of course cost implications.

CONCLUSION

GaN HEMTs are now delivering outstanding RF power and reliability. In this paper the key reliability and performance issues specific to these devices have been identified. They have been controlled or suppressed by a combination of device design (eg field plates and gate shaping), epitaxial growth (eg controlled doping using materials such as iron), and process changes (eg appropriate passivating layers and the choice of gate metals). The result is a highly robust technology which is rapidly displacing traditional solid-state power technologies.

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