Dielectrics for GaN and GaN as dielectric:
The role of interface and bulk defects

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Abstract

We summarize the current understanding of the interface between GaN and dielectric materials as found in MIS gate stacks or passivated surfaces. Therein we will discuss the role of the native donor states responsible for the 2DEG and the acceptor-like defects causing device drift. Further we will discuss the underlying physical model of insulating GaN doped with Carbon. We show that structural defects are likely to cause a C-related defect band rendering GaN:C a lossy dielectric.

1. Introduction

Gallium nitride based semiconductor materials have shown great potential for power applications due to the large bandgap of 3.4 eV and its high mobility in case of AlGaN/GaN heterostructure devices. Due to cost and thermal reasons those III-N epitaxial layers are typically grown on (111) Si substrates as shown in figure 1. The substrate is then connected to source via an external connection through packaging. It is interesting to note that due to the high band gap of GaN, minority carriers are often not important for the device behavior. In fact, most parts of the device (Fig. 1), except the 2-dimensional electron channel below the AlGaN barrier, is depleted from free charge carriers. However any existing charge states in the surrounding area (GaN channel and buffer, passivation and Gate dielectric) are prone to be charged or discharged during device operation. Most commonly drift behaviors seen in such devices are positive drifts of the threshold voltage, increase of the drain-source resistance and decrease of the on-state current.

In this presentation we will summarize the current understanding of defect states at the III-N/dielectric interface and C-related defects in the buffer. Interestingly both types of defects are not just defects that one would like to avoid and therefore minimize

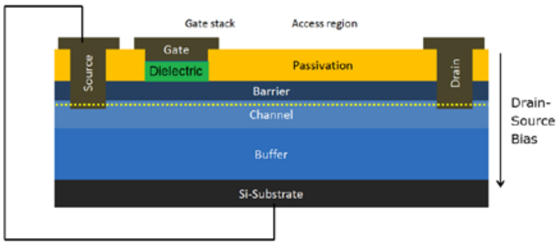

Fig.1: Schematic of GaN Power device with MIS gate. The Si substrate is connected to source by the bonding scheme during packaging.

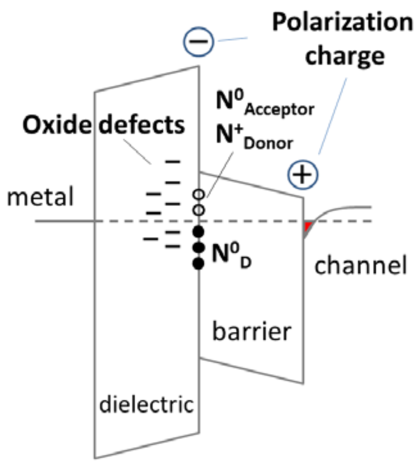

Fig.2: Band diagram of gate stack consisting of AlGaN barrier and dielectric layer. Also included are the polarization charges as well as donor- and acceptor-like defect at the dielectric interface and the dielectric (oxide) layer.

in quantity. Both defects are in fact responsible for important features of the device behavior as well.

Donor-like interface states are the key in AlGaN/GaN devices to enable a 2-dimensional electron gas (2DEG) below the AlGaN barrier. We will discuss the interesting case that those donor states do not participate in any transient effects observed in AlGaN/GaN MIS-HEMTs. We are able to derive this conclusion by studying the threshold voltage drift under forward and reverse gate stress. It turns out that a certain type of acceptor-type interface states rather than the donor-states seem to be responsible for trapping at the interface. Careful investigation by stress-recovery measurements shows that the defect density is likely larger than the number of detectable charges limited by the breakdown field of the dielectrics [1].

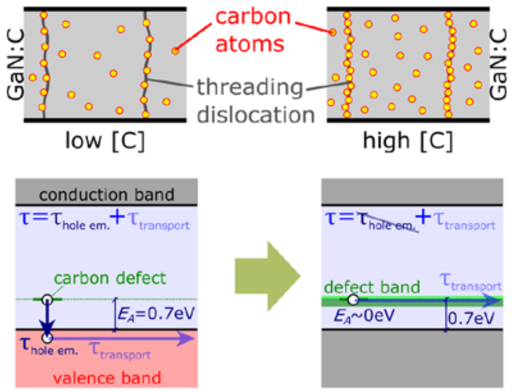

Fig.2: Schematic of C-related mechanism to render GaN a dielectric. The top two figures show a low and a high C scenario in which both C tends to segregate to dislocations. In the low C case the distance between C atoms is wide enough such that the C defects act as individual traps (bottom left band diagram). For a certain higher concentration of C, sufficient interaction between C atoms can be found, resulting in a C-defect band. This model of a basically lossy dielectric GaN is shown in the bottom right.

In the second part we will discuss the particular role of Carbon, which is a necessary dopant in the GaN buffer to create an insulating buffer characteristic. It has been shown that Carbon can act as donor state or deep acceptor. Most reports find the Fermi-level about 0.6-0.9 eV above the valence band, which indicates a dominant behavior of the latter one. However, up to very recently it was not clear how deep acceptors can effectively pin the Fermi-level due to expected long hole emission and capture times. Our investigations have shown that the acceptor-like defects form a defect band (Fig.2) with a lossy dielectric-like leakage behavior. This lossy layer is able to form a sufficiently high barrier for electrons and holes resulting in leakage current reduction. Further, the lossy link between the C defects removes most of their transient drift behaviors allowing today GaN buffers with minimal contribution of dynamic device effects [2].

2. Experimental

The fundamental method used in all of our investigations is a transient current and capacitance measurement after a defined stress. These so called stress-recovery or measurement-stress-measurement techniques allow the recording of defect response with a wide range of capture and emission times. Both current and capacitance transients can be recorded only a few micro-seconds after the stress pulse.

The MIS-HEMT devices were characterized by drain current transients after a gate voltage stress pulse [1]. In case of GaN:C, we developed a special structure were a thin layer of C-doped GaN has been placed between a low-doped GaN:Si (n-type) layer and a metal contact [2]. This “MIS-like” structure can be investigated similar to any gate stack with the purpose of characterizing the dielectric layer (here GaN:C) by measuring the depletion of the n-GaN layer.

3. Discussion and Conclusions

The threshold voltage drift characteristic observed under forward gate bias stress indicates the existence of an ensemble of acceptor-like defects at the interface with a broad distribution of capture and emission time constants. This result does unfortunately not allow any further unambiguous extraction of physical parameters of the involved defects. Defining a worst-case lifetime model for threshold voltage drift for normally-off MIS-HEMTs we believe that currently no dielectric layer is capable of rendering a sufficiently low defect density.

All the observed drift behaviors are only recognized in forward gate bias stress. Hence we assume that donor states are not involved as they should cause similar drift effects in negative gate bias stress. We were able to produce a particular modification of the native donor states with a very fast capture and emission time that proofs this case.

Regarding the GaN:C characteristic we find a common non-Arrhenius T-dependency for charge trapping, de-trapping as well as the leakage current. Besides defect interaction with conduction or valence bands we consider the carrier exchange with the defect band (Fig.2), which can explain a wide range of activation energies found previously for C in GaN.

In conclusion, GaN devices have now entered a technological maturity where defects are no longer seen as unwanted participants in a layer but their active role in controlling the device behavior is understood and can be used to optimize devices.

References

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