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The impact of buffer design on GaN HEMTs

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Abstract

GaN HEMT epitaxy is always doped with deep levels to suppress off-state leakage, however this can also lead to bulk related current-collapse. It is shown that intentionally or unintentionally incorporated carbon leads to a p-type buffer for both RF and power switching devices. Suppression of current-collapse then requires a parallel leakage path in threading dislocations to prevent the build-up of negative charged depletion regions in the gate-drain region. Control of bulk vertical and lateral hole transport is critical for high performance devices.

1. Introduction

Conventional GaN HEMTs require a semi-insulating layer below the 2DEG to suppress off-state leakage and short-channel effects. This is normally achieved by adding a deep acceptor such as iron or carbon, with the assumption that this will pin the Fermi level and allow the buffer to be treated as an insulator. However, the semi-insulating layer is actually electrically active on a range of different timescales, and needs a detailed understanding and management of the dynamics of trapping, leakage and trap density to deliver high performance. Suppression of dynamic R_{ON} and current-collapse requires a constant resistivity bulk under static conditions (charge can only accumulate where there is a change in resistivity – the Maxwell Wagner effect)[1]. Hence successful buffer design corresponds to avoiding charged depletion and accumulation layers.

The requirements for RF and power switching epitaxies to suppress buffer trapping related issues like dynamic R_{ON} and current-collapse are quite distinct, but are linked by the need to understand and control the role of carbon and leakage along threading dislocations.

2. Power Switching HEMTs

650V GaN-on-Si HEMTs normally use the epitaxial design below the 2DEG shown in Fig. 1. At normal operating voltages, it is charging/discharging of the carbon doped layer (GaN:C, ~10^{19}cm^{-3}) which controls dynamic R_{ON} and current-collapse. So suppression of dynamic effects on all timescales requires control of the resistive and capacitive network shown in Fig. 1. Carbon on the nitrogen site has an acceptor level (0/-) 0.9eV above the valence band and at the high densities employed is self-compensated, strongly pinning the Fermi level. At 10^{19}cm^{-3}, transport occurs by defect band conduction resulting in a weakly temperature dependent resistivity of >10^{11}Ohm.cm[2], with almost all charges residing in narrow depletion layers on the surfaces of the carbon doped layer. Crucially the layer is p-type so the GaN:C layer is isolated from the 2DEG by a P-N junction, and hence its potential can float. In reality its potential is defined by the reverse bias leakage path from 2DEG to GaN:C layer occurring via the threading dislocations[1]. Drain bias would result in negative and positive charged regions in the GaN:C as shown in Fig. 2, however increasing the leakage leads to the reduction of dynamic R_{ON} by suppressing the unwanted negatively charged region. The impact of varying the number of leakage paths on dynamic R_{ON} is shown in Fig. 3, with higher leakage leading to suppression of current collapse and ultimately a negative dynamic R_{ON}[3]. The magnitude of the hole leakage required to suppress the dynamic R_{ON} is very small and hardly impacts the drain leakage current in the pA range (Fig. 4). Suppression of dynamic R_{ON} is largely a matter of controlling this leakage path, the route to which is proprietary but can be achieved by either processing or epitaxy.

3. RF Power HEMTs

RF GaN-on-SiC HEMTs are usually doped with iron which has an acceptor level 0.6-0.7eV below the conduction band, so one might expect it to be n-type. Memory effects during the MOCVD epitaxial growth result in an exponential drop in Fe density towards the surface from a peak value >10^{18}cm^{-3}. However equally, if not more importantly, there is always a carbon background in the 10^{16} to >10^{17}cm^{-3} range. If the carbon acceptor density exceeds that of any intrinsic donors, as is frequently the case, the Fermi level will reside on the C level, the bulk of the GaN will be p-type, and the Fe will all be neutral except for a small insignificant region near the 2DEG where the Fermi level crosses the Fe trap level[4]. Hence it is frequently the background C and not the Fe which controls the electrical properties of the semi-insulating epitaxy, even if its density is well below the density of the Fe.

In contrast to the power switching case, the C density is much lower so the transport is expected to be by free holes in the valence band, the Fermi level is not strongly pinned to the C acceptor level, and depletion region widths can be comparable to the GaN epitaxial layer thickness. One direct consequence of a p-type bulk is that charging/discharging of the depletion region under the drain leads to a "kink effect" which is strongest for higher background C density[5]. For C density in the 10^{17}cm^{-3} range, charging of this depletion region leads to an increase in drain resistance and a resulting knee walkout and current-collapse. As for power devices, this could be suppressed by modifying the vertical leakage along dislocations

(Fig. 5), reducing the voltage drop across the depletion region leading to a thinning of the depletion region (Fig. 6).

4. Conclusions

Carbon, either intentionally or unintentionally incorporated, leads to a p-type GaN layer under the 2DEG in both power and RF devices, which in turn leads to current-collapse associated with charged depletion regions. Suppression requires that the depletion region leakage becomes comparable to the bulk transport, preventing the build-up of charge in depletion regions in the bulk. Far more attention needs to be devoted to background carbon than is currently the case for RF devices, and for all devices the role of threading dislocation leakage is critical and needs careful control.

Acknowledgements

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References

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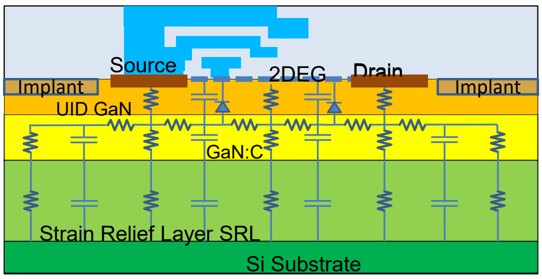

Fig. 1. Equivalent circuit representation of 650V GaN-on-Si power switching HEMT.

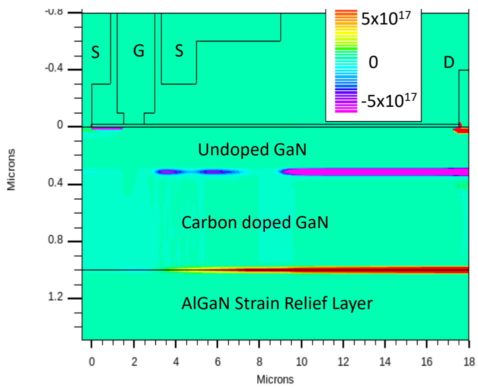

Fig. 2. Simulated net charge density (cm^{-3}) at V_{DS}=300V, V_{GS}=-5V, $10^8 cm^{-2}$ dislocation density. GaN-on-Si HEMT.

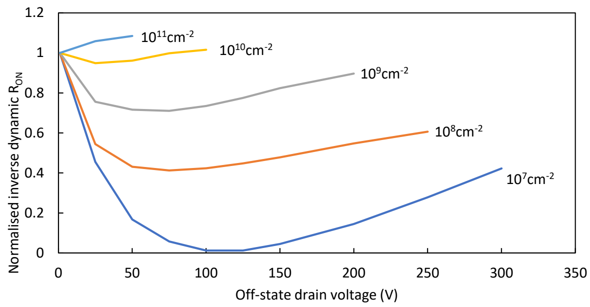

Fig. 3. Simulated inverse dynamic R_{ON} of 650V GaN-on-Si HEMT for varying nominal dislocation density.

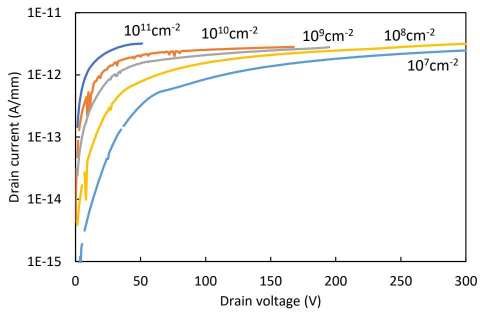

Fig. 4. Simulated off-state leakage current of 650V GaN-on-Si HEMT for varying dislocation density.

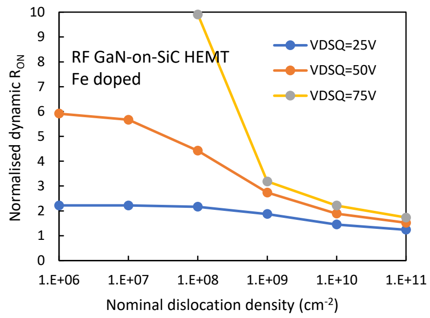

Fig. 5. Simulated dynamic R_{ON} at off-state drain bias from 25 to 75V versus dislocation density for Fe doped, $3x10^{17}cm^{-3}$ carbon, RF GaN-on-SiC HEMT.

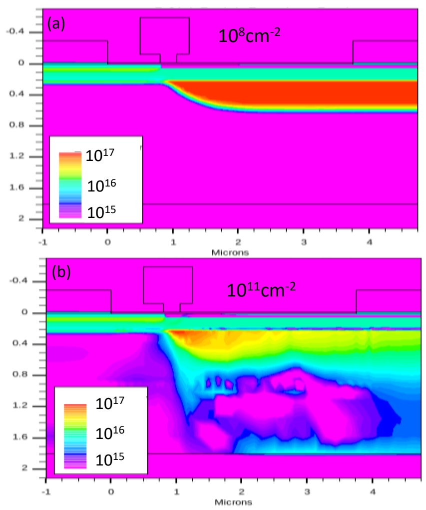

Fig. 6. Simulated net charge density (cm^{-3}) at V_{DS}=25V, V_{GS}=-3V, (a) $10^8 cm^{-2}$, (b) $10^{11} cm^{-2}$ dislocations. Contours on log scale from 10^{15} to $10^{17} cm^{-3}$.