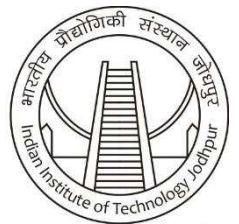


Modeling and Simulation of Gallium Nitride High Electron Mobility Transistors and Optimization of Buffer Layer

A Thesis submitted by
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in partial fulfillment of the requirements for the award of the degree of
Doctor of Philosophy



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Indian Institute of Technology Jodhpur
Electrical Engineering
July 2018

Conclusions and Future Scope

Being the most promising candidates to satisfy the growing demands of power and semiconductor market, AlGaIn/GaN HEMTs were analyzed in this work with the aim to develop a computational strategy to estimate device performance. The computational framework thus developed led to the understanding of behavior of C-Doping in GaN buffer and facilitated proposal for achieving ultra-high breakdown voltages without compromising on device performance by optimized buffer doping. This work also lays down the foundation for computational analysis-based proposal for buffer designing in AlGaIn/GaN HEMT devices, opening the way for several possible future extensions and device optimizations. This chapter discusses the learning outcomes of this thesis work and discusses the future scopes.

6.1 SUMMARY

With the aim of enabling rapid technological development in AlGaIn/GaN HEMTs computational strategy was developed in this work along with a discussion on GaN buffer designing in AlGaIn/GaN HEMTs. A summary of the work carried in this thesis along with the learning outcomes is as following:

- I. Physical parameters required to model behaviour of AlGaIn/GaN HEMT devices were comprehensively discussed and presented with the associated model to accurately predict the device characteristics.
- II. In order to predict the DC behaviour of the device, it was shown that:
 - a) Polarization induced charges need to be accounted at all the material interfaces to account for any parasitic charges present in the device.
 - b) Donor traps at the device surface greatly influence the 2-DEG channel and are essential to be considered to model the behaviour of device surface.
 - c) Gate leakage, for Schottky gated device, was proposed as an effective tool to derive the surface trap parameters. In addition to this, gate leakage was found to be dependent on the device geometry and needs a careful investigation of the placement of gate pad and gate metal to estimate any secondary leakage paths.
 - d) Acceptor type traps in GaN buffer, are essential to be considered due to their impact on 2-DEG channel. However, they were shown to be not the source of NDR phenomena observed in output characteristics of AlGaIn/GaN HEMTs.
 - e) Quantum confinement had a significant impact on 2-DEG profile and density. However, negligible impact was seen on the device characteristics as the reduction in 2-DEG density was compensated by a corresponding increase in channel electron mobility.
 - f) Contact modelling was also found to be of significance due to complex behaviour of alloy formation and associated chemistry resulting from post deposition anneal of gate metal stack. Particularly, the contact resistance was found to affect the linear as well as saturation characteristics of the device.
 - g) Finally, device self-heating was found to have a significant impact on device characteristics and is essential to modelled to take into account the NDR effect

observed in output characteristics of the device. In addition to this, it was shown that it is essential to take into account the carrier heating or hot electrons to account for velocity overshoot effect as well as trapping de-trapping in surface and buffer traps.

III. In order to have an optimum design of the GaN buffer, carbon doping of GaN buffer was analysed with respect to its impact on avalanche breakdown of the device. The findings of the study can be summarized as follows:

- a) Carbon essentially behaves as trap in GaN. C replacing N behaves as acceptor site and is responsible for increase in buffer resistivity. It however is unable to explain the experimentally observed improvement in avalanche breakdown with C-Doping of GaN buffer.
- b) While C taking up N site behaves as acceptor trap, on the other hand, C replacing Ga can behave as donor trap. It is the presence of C as donor trap site that results in vertical field relaxation and hence improvement in breakdown voltage.
- c) C behaving as self-compensating traps explains the impact of C-Doping on breakdown voltage.
- d) Design optimization showed that the breakdown voltage can be maximized even with a reduced acceptor trap concentration, provided that the donor trap concentration is maintained at the maximum possible value.

IV. Based on the understanding that breakdown performance can be maintained even with a lower acceptor trap concentration provided that the donor trap concentration is maintained, a novel doping technique was proposed for the GaN buffer to maximize the breakdown performance. Results of the same are as follows:

- a) While C has a higher probability to behave as acceptor traps in GaN buffer, Si is known to behave as n-type dopant in GaN. Thus, C dopant can be seen as a source of acceptor traps, while Si dopant can be seen as a source of donor traps.
- b) Thus, co-doping of GaN buffer simultaneously by C & Si provides the designer with a method to independently control acceptor and donor trap concentrations.
- c) Co-doping of GaN buffer by C & Si, was proposed and backed by physical explanation to result in a similar breakdown voltage improvement with reduced requirement for C-Doping concentration.
- d) The independent control of acceptor and donor traps concentrations in GaN buffer led to a proposal to modify buffer doping profile to result in an optimized device performance with ultra-high breakdown voltage.

6.2 CONCLUSION

The different experiments carried out in this thesis and the learning outcomes highlight the requirement of an exhaustive approach to carefully integrate physical models in computational framework to estimate device performance of AlGaIn/GaN HEMT devices. The observations with respect to C-Doping in GaN buffer clearly outline the requirement of proper understanding of different physical mechanisms involved with AlGaIn/GaN HEMTs. C-Doping fairly improves the voltage handling capacity of the device by redistributing the electric field. However, the primary source of this field relaxation arises from the C dopant behaving as donor trap site in GaN buffer whereas its behavior as acceptor trap controls the buffer resistivity. However, the higher probability of C behaving as acceptor trap site in GaN buffer results in incorporating a relatively higher acceptor trap concentration as compared to that required for achieving the required breakdown voltages. Through computational analysis it was established that controlling the donor concentration by Si-Doping while using C as a source for acceptor traps can effectively help in relaxing the requirement for C-Doping. The Si-C co-doping technique

results in achieving ultra-high breakdown voltages while maintaining a lower acceptor trap concentration in GaN buffer. The proposed buffer doping technique is expected to result in a dramatic improvement in device performance, especially for devices requiring higher voltage blocking capability. In addition to this, reduction in traps in the GaN buffer is expected to improve the RF performance and reliability of the device as well.

6.3 FUTURE SCOPE

This thesis work addressed a wider domain of computational analysis of AlGaIn/GaN HEMT devices by establishing a computational modeling strategy to estimate DC performance of AlGaIn/GaN HEMT devices. While explaining behavior of C-Doping in GaN buffer, the thesis addressed the larger issue of GaN buffer designing in high breakdown voltage enabled AlGaIn/GaN HEMT devices by Si-C co-doping of GaN buffer. While the thesis work fulfills its objective of providing a reliable buffer designing technique to improve device performance, however the wider framework discussed in this work is not limited to the studies presented in this work and retains possibility of extension to several other dimensions enabling computational analysis based rapid technological development in AlGaIn/GaN HEMT devices. Some of the possible extensions to this work are discussed as follows:

- I. While this work largely addresses the DC performance of the device, the advanced computational framework discussed here can be extended to include RF performance of the device. However, taking into consideration the complex behaviour of traps in the HEMT devices and their pronounced effect on 2-DEG channel, estimating RF performance of the device is a complex problem.
- II. Having a reliable and adaptive framework for estimating RF performance of the device can provide an effective tool to further project the RF performance of the device with modified buffer doping as proposed in this work.
- III. While Si is well known to behave as n-type dopant in GaN, its effect on channel mobility of AlGaIn/GaN HEMT is not well understood and is a limiting factor in estimating device performance under the proposed buffer doping conditions. An experimentally derived channel mobility for Si-Doped GaN buffer can help in making the calculations more practical.
- IV. Traps on device surface and GaN buffer are the source of major reliability concerns in AlGaIn/GaN HEMTs. While the impact of traps in GaN buffer on avalanche breakdown has been extensively discussed in this thesis, a discussion on impact of surface quality on the same can provide a complete overview of the growth related optimization for achieving ultra-high breakdown voltage in AlGaIn/GaN HEMTs.
- V. Finally, the computational framework discussed here and the analysis techniques presented can be extended to discuss device-circuit co-design for AlGaIn/GaN HEMTs providing an all-inclusive solution to rapid technological adaptation of GaN HEMT technology.

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