Department of Electrical Engineering, National Tsing Hua University
Special Topic on Implementation Research Abstract

Passive Substrate Termination of Bidirectional GaN HEMT
氮化鎵雙向元件基材電位的被動控制

Major Category: 電子領域

Group Number: B479

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Abstract

Gallium Nitride High-Electron-Mobility Transistors (GaN HEMTs) are gaining significant attention in the power electronics industry. Recent advancements have proven promising advantages of GaN-on-silicon transistors. Despite their excellent performance, GaN-on-Si HEMTs face challenges such as increased dynamic on-resistance caused by trapped negative charges in the substrate. Literature showed that proper control over substrate bias addresses this issue. Controlling the substrate bias for unidirectional GaN HEMTs can be straightforward, typically by shorting the substrate to the source terminal. However, this approach is incompatible with bidirectional GaN HEMTs with common drift region because the low voltage side depends on the operation mode. This research proposes a passively operating substrate bias control scheme with verification of its performance using a substrate trapping effect model.

Introduction

Background & motivation

Bidirectional switches are commonly used in various power electronics applications, such as T-type inverter, Matrix converter, Vienna rectifier in three phase power factor correction (PFC) circuit etc. The presence of these types of switches is due to the need for voltage blocking capabilities for both directions, and that’s what a unidirectional switch cannot do. Due to the high voltage blocking capability and the low turn on resistances of GaN HEMTs, they are being used in these high voltage rating systems. However, trapped charges in the substrate will induce back gating effect and degrade the dynamic on resistance of GaN HEMT. This will decrease the efficiency of power conversion and limit the gains from using GaN HEMTs.

To address this issue, we need to control the substrate bias of the bidirectional GaN HEMT but since we have no fixed low voltage terminal we need to design a method to be able to short the substrate to low voltage side depending on the operation condition. Therefore, there is a need to research and develop a way to properly control the substrate bias of a bidirectional GaN HEMT with common drift region so that the dynamic on resistance can be maintained at low level and the advantages of GaN HEMTs can be fully utilized.

Purpose

The purpose of this comprehensive research is to study the trapping effect in the bidirectional GaN HEMT, build a trapping effect model for its substrate and find a solution to solve the issue. We are going to focus on the common drift region configuration (Fig. 1) specifically because it has half the value of turn on resistance when compared to other configurations.

The need to build a model representing the trapping effect in the substrate is due to the lack of spice models representing this monolithic bidirectional device on the tape out platform. This substrate model will be used to evaluate the performance of our solution and the performance of other solutions.With the help of this model, we aim for a low power, fully passive control circuit that can properly bias the substrate of the bidirectional HEMT, which will lead to maintaining the low dynamic turn on resistance of the bidirectional GaN HEMT. Vigorous simulation and evaluation will be done to verify the design is less likely to cause failure before the design goes to the tape out process.

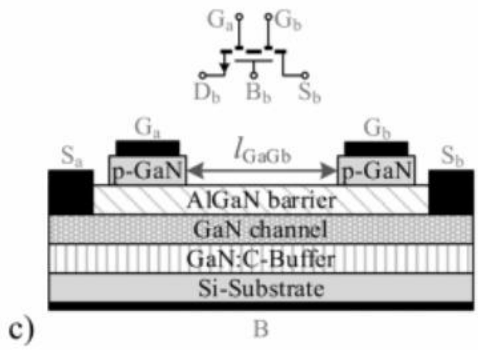

Fig. 1 Common Drift region configuration of monolithic bidirectional GaN HEMT [5]

Research Method

The research method is done by a process of determining the specifications, substrate model design, substrate bias control scheme development.

2-1. Developing the specifications

The specifications a developed based on various data collected such as operating frequency when it is being used in systems, limit of rise time and fall time of a GaN device, effect on substrate bias on the dynamic Rdson value etc. and we summarize the specifications into this table (Table 1)

Table 1

Specs Used for Developing the Control Scheme

Item	Value
Substrate bias	Follow the lower voltage among S1&S2
Blocking voltage	50V 300V 600V
Frequency	Order of 100kHz
Rise time and Fall Time	10ns
Reference point for voltages	No extra references except from the original 4 terminals (S1, S2, G1, G2)

2-2. Substrate Model Design

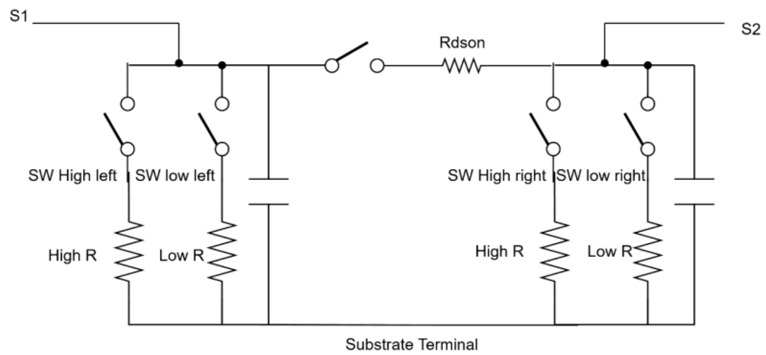

Fig. 2 Model for Representing the Substrate of a Bidirectional HEMT

The model is an extension of the unidirectional GaN HEMT substrate model in literature [7]. With the use of data of the device itself we use methods to determine the corresponding R and C in the model and make the switches to switch accordingly to mimic the trapping effect.

2-3. Substrate bias control scheme developement

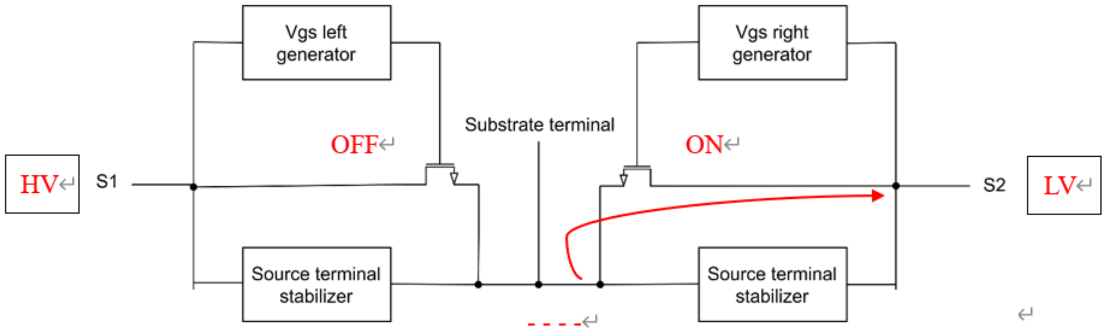

Fig. 3 The proposed solution

The control scheme is developed by finding creative ways to short the substrate to the lower voltage terminal is designed and evaluated carefully in simulation and consultation from professionals.

3. Results

3-1 Model for substrate trapping behavior

We can see that the resultant substrate voltage from the model shifts to negative (Fig. 4) after the switching events. It mimics the behavior of negative charges trapped in the substrate and we successfully developed a simplified model that is useful for developing a substrate bias control scheme.

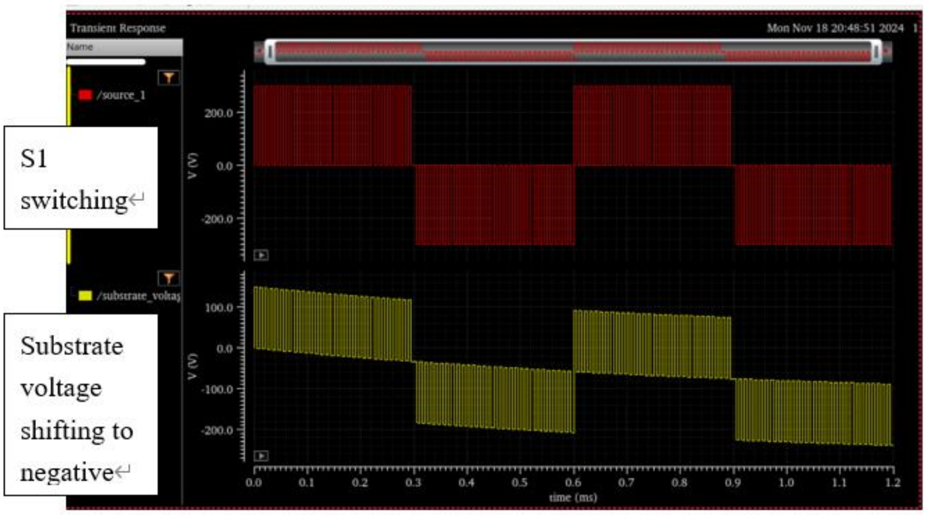

Fig. 4 Model shows the trapping effect in the substrate

3-2 Performance of the substrate bias control scheme

Table 2
Performance of the substrate bias control scheme

Blocking voltage	Power	Vgs generator output		Substrate bias	
		HV Side Vgs	LV side Vgs	Blocking state (OFF)	On state
600V	5.2mW	3.2V	0V	0V	-20V
300V	2.62mW	3.42V	0V	0V	-20V
50V	0.25mW	3.42V	0V	0V	-10V

The On State substrate voltage is following the lower voltage among the two sources alt hough not exactly at the same but it is considered as a great improvement from the TI su bstrate bias clamping scheme because it will induce of -1/2 * HV negative voltage in su bstrate, which translates to approximately -300V if 600V blocking voltage is applied. There is also good improvement in terms of power and hardware when compared to the active substrate termination scheme [5], because we don't need to operate two drivers to control the substrate voltage furthermore, we don't need to use a floating voltage suppl y to operate these drivers. The comparison is concluded in Table 3.

Table 3

Comparison of This Work to Other control scheme

Items	**TI scheme**	**Active substrate termination scheme [5]**	**This work**
Number of drivers for control scheme	0	2 drivers, 1 floating power supply needed	0
Substrate voltage at off state (600V)	Vth	0V	0V
Substrate voltage at on state	-300V	0V	-20V (can be improved to near 0V)
Power	smallest	Largest	Middle (order of mW)
Rise & fall times	10ns	>10ns due to gate resistor, parasitic inductance	10ns

With verification and simulation, we have done a lot of simulation to find out the performance of the design and the design is ready for tape out. Till then, we will do verification on the design.

4. Conclusion

Throughout this research, we have achieved a few things:

1. We build a model to represent the trapping behavior of the bidirectional HEMT.
2. We have developed a substrate control scheme without need of external control this makes the substrate to be controlled near the lowest voltage among the two sources.
3. The control scheme can operate under extremely short rise time and fall time (10ns) which is near the limit of GaN transistors' rise and fall time limit.
4. The autonomous scheme has a dedicated design to prevent fault turn on of the substrate switches.
5. The scheme has significant immunity to the voltage oscillation at the HV side.

5. Review and reflections

The research is a fulfilling experience for me, throughout this process I have learned a lot of very specific knowledge about Gallium nitride transistors. I wouldn't have known that these transistors have that much potential, if I didn't join this research. It definitely has broaden my knowledge about the semiconductor industry, and I start to understand how an electrical or electronic device is being developed, manufactured and tested.

I am also given the opportunity to learn about semiconductors process and understand how a transistor works on a fundamental level. With the guidance of my advisor, I tried to learn how he perceives things and try to learn the way he deals with problems that appear during a research process. That's very fruitful training because we are able to work with professionals and learn from their experiences.

Most of all, it made me become more passionate about this industry and it made me want to continue with research tasks in the future.

6. References

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