Department of Electrical Engineering,
National Tsing Hua University

Special Topic on Implementation
Research Summary

GaN-on-Si Bi-directional power HEMT development

氮化鎵在矽基板雙向功率高電子遷移率電晶體開發

Major Category: 電子領域

Group Number: B433

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Abstract

Gallium Nitride represents a highly promising wide band-gap semiconductor material, offering many benefits in terms of device performance and efficiency. A key characteristic of GaN devices is their capability to handle higher voltages, attributed to their high critical electric field compared to Silicon. Additionally, these devices can reduce on-resistance and enhance switching speeds. The adoption of GaN High Electron Mobility Transistor in the field of power electronics has attracted significant interest, driven by the demand for improved efficiency and performance in power systems. This project is focused on the development of a monolithic Bi-directional GaN Power Switch, designed to operate across all four quadrants, making it particularly advantageous for applications such as electric vehicle chargers and telecommunications systems, where high efficiency and compact design are critical.

Our research began by using the structure of an existing GaN power device and trying to analyze the device structure. We used TCAD simulations to recreate the features of a single-gate GaN power device. After confirming the basic structure, we added a field plate and a second gate to test how a bi-directional device would perform.

A key technical challenge in this project was finding the right balance between breakdown voltage and switching performance. High breakdown voltage allows the device to handle high-voltage operations, while low specific on-resistance is important for reducing energy loss. Through TCAD simulation, we can explore key design choices, like the trade-offs between breakdown voltage, switching speed, reliability, and specific on-resistance, which are all essential for an efficient and reliable BGPS.

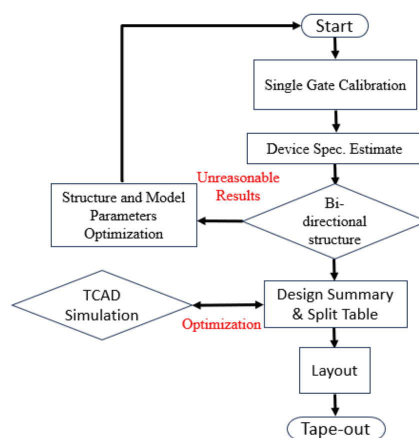
In the end, we successfully matched the output capacitance of the device, confirming the accuracy of our design. The Bi-directional GaN Power Switch we developed in TCAD simulations aligns closely with theoretical expectations and previous research, supporting the reliability of our design. The next step is to prepare for tape-out, which will allow us to build the actual device and verify our results with real measurements. These tests will give us additional insights to further refine the device in the future.

Background and Purpose

The continuous advancement of power semiconductor technology has made Gallium Nitride a crucial material for high-performance power electronics, primarily due to its wide bandgap properties. GaN enables devices to operate at higher voltages, frequencies, and temperatures compared to traditional silicon-based semiconductors, making it ideal for next-generation power applications. GaN-on-Silicon technology offers a promising solution, merging GaN's superior performance with the cost-efficiency of silicon. This project focuses on developing a GaN-on-Si-based Bi-directional Power High Electron Mobility Transistor to meet the growing demands for high-efficiency power conversion systems.

The primary objective of this project is to design a GaN-on-Si Bi-directional Power HEMT. Due to lateral architecture of GaN power semiconductors enables the development of a monolithic GaN HEMT, which can conduct current in both directions, meeting the requirements for high-voltage and high-frequency applications. This innovative design reduces conduction losses in applications like multilevel T-type inverters, where bidirectional voltage blocking is critical. Furthermore, this device can offer comparable switching and on-state behavior to conventional unidirectional GaN HEMT.

Method



1. **Single Gate Calibration**: The process begins with the calibration of a single-gate GaN power device. This step ensures that the structure built on TCAD accurately and the device characteristics are tuned. This calibration is critical before progressing to more complex structures, as it ensures the model closely aligns with real-world performance.

2. **Specification**: Based on the single-gate calibration, we estimate the necessary specifications for the bi-directional structure. This includes key factors such as voltage ratings, current density, and switching characteristics. Significant trade-offs need to be considered, for example, the length of the gate-to-gate, which will influence both the breakdown voltage and on-resistance. Additionally, the length of the field plate and its combination will impact the breakdown voltage and capacitance. These trade-offs are carefully balanced to optimize device performance while meeting the required operational conditions.

3. **Bi-directional Structure Development**: The bi-directional HEMT structure is initially proposed and evaluated through simulations. If the performance or specifications are found to be unreasonable, we revert to the single-gate device, making necessary adjustments based on the modifications required for the bi-directional device. This iterative process of recalibration and optimization ensures that while developing the bi-directional device, the single-gate device remains the reference parameter for comparison and validation.

4. **TCAD Simulation and Design Summary**: Throughout this process, the structure is optimized by adjusting device parameters and using TCAD tools to guide further optimization to enhance performance.

5. **Layout**: We will create the mask for the layout based on the split table we previously developed. Additionally, we must ensure that our layout follow all fabrication rules and guidelines.

6. **Tape-out**: Finally, the optimized design is sent for tape-out, the stage where the device is ready for fabrication and testing in a real-world environment.

Results

- **Device Structure**

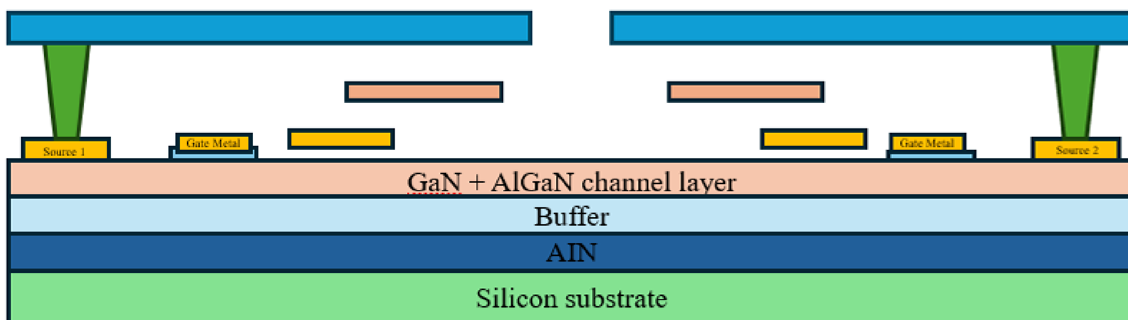


Figure 1: propose device structure

In a GaN HEMT, current flows between the Source 1 and Source 2 through an active AlGaN layer positioned directly beneath the source 1, source 2, and gate. This layer forms a two-dimensional electron gas at the interface between the AlGaN active layer and the GaN channel layer. The 2DEG is a dense layer of free electrons, which enables high-speed and efficient current flow across the device when voltage is applied. This AlGaN/GaN heterostructure allows GaN HEMTs to achieve fast performance and handle large currents, making them particularly suited for power applications.

The buffer structure bellows the active region consists of several carefully arranged layers that enhance the device's stability and performance. The structure transitions through a series of intermediate layers to create a stable interface with the underlying substrate. This layered configuration reduces lattice mismatches between the materials, minimizing imperfections and

ensuring reliable performance under high-voltage conditions. The buffer stack is critical to the functionality and long-term reliability of the bi-directional HEMT.

The device also uses a three-layer field plate structure. These field plates play a critical role in reshaping the electric field distribution along the channel. By optimizing the electric field profile, the field plates can increase the breakdown voltage, which is essential for stable, high-voltage operation in power applications.

- **Device Operational Mode**

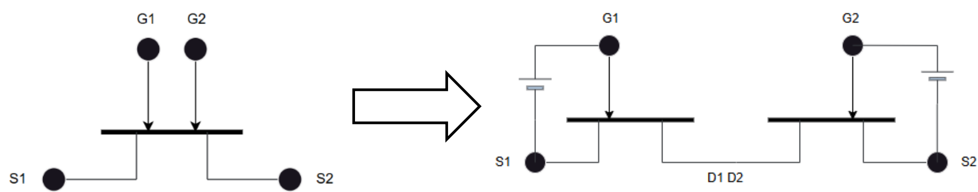


Figure 2: Dual-Gate Bi-Directional GaN HEMT

The dual-gate Bi-directional GaN HEMT functions as two GaN FETs connected in a back-to-back common-drain configuration. This design allows the device to control current flow in both directions depending on the gate-source voltages applied to each gate.

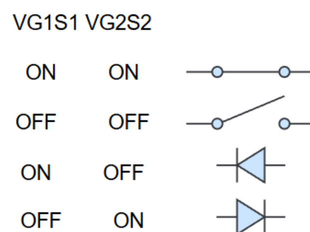


Figure 3: Operation modes of Bi-Directional GaN HEMT

There exist 4 modes of operation for this device forward conduction, reverse conduction, forward blocking, and reverse blocking, depending on the VGS values. This dual-gate configuration enables four-quadrant operation, meaning the device can manage positive and negative current and voltage conditions.

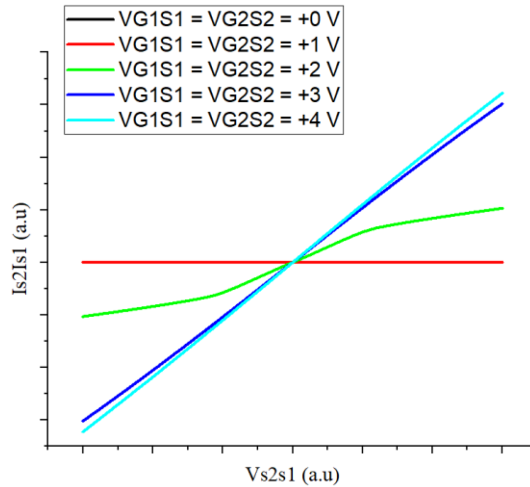


Figure 4: Bi-directional mode output

The device's operating mode can be adjusted in practice by altering the gate-source voltages, VG1S1 and VG2S2. For example, in bi-directional mode, if VG1S1 and VG2S2 are both set to the "on" condition, the device permits current flow in both directions between source and drain. Conversely, setting VG1S1 or VG2S2 to "off" creates a blocking state, effectively preventing current flow.

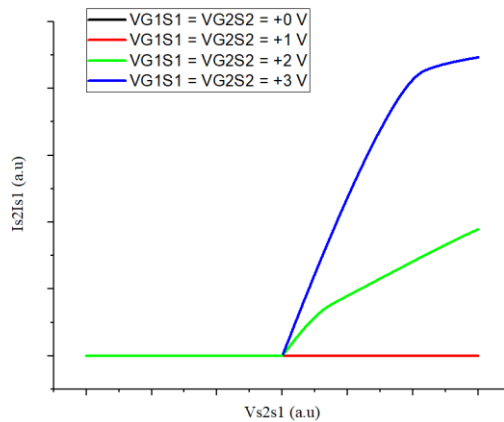


Figure 5: Single-directional mode output

In single-directional mode, the device can function similarly to a traditional diode, where current flows only when the voltage on S2 exceeds that on S1 (i.e., VS1 < VS2), and it blocks current flow in the reverse condition.

- **Electric Field Distribution**

The field plate structure is essential for enhancing the breakdown voltage in bi-directional GaN devices we need to manage the electric field distribution effectively. By altering the electric field between the gate and channel region, the field plate reduces peak field intensity near the gate edge, improving device reliability and breakdown voltage.

The design of the field plate is particularly important, as the electric field at each corner of the field plate can reach saturation, which defines the maximum electric field that the field plate can handle. Moreover, consideration of field plate positioning is critical to ensuring an even field distribution, minimizing peak values. Simulations can help us confirm that a well-optimized field plate design significantly improves the device's performance under high-voltage conditions.

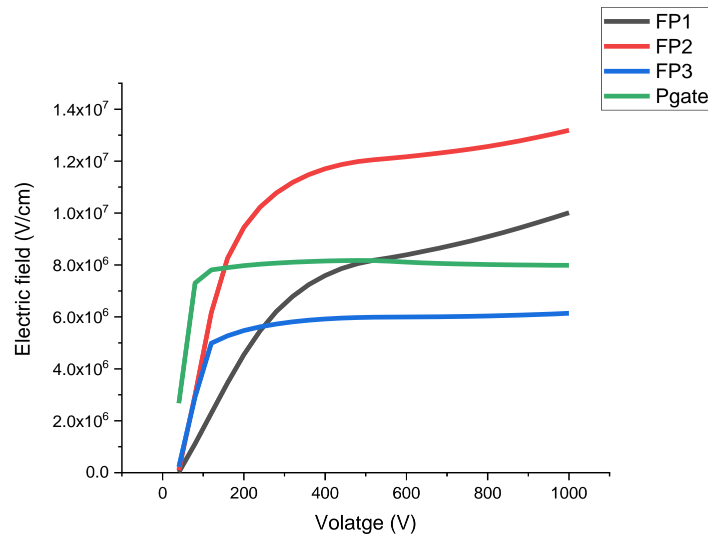


Figure 6: Electric Field distribution at each corner of Field plate

- **Optimization**

In optimizing the bi-directional GaN device, TCAD simulation plays a critical role in identifying and fine-tuning key design parameters to achieve optimal performance. One of the primary factors analyzed is the gate-to-gate distance, which affects both breakdown voltage and on-resistance. Simulations show that increasing the gate-to-gate distance enhances breakdown voltage by reducing the electric field concentration at the gate edge. However, a longer distance also extends the channel region, which raises the on-resistance due to the increased current path.

Additionally, Field Plate length and combination are optimized using TCAD to control breakdown voltage and manage capacitance. By adjusting the FP length and combinations in the simulations, it's possible to disperse the electric field more effectively across the device,

which raises breakdown voltage while minimizing capacitance. A lower capacitance contributes to faster switching speeds, which is critical for high-frequency applications.

Conclusion

In conclusion, this project successfully achieved the design and simulation of a monolithic Bi-directional GaN Power Switch that can function in four-quadrant operation for power applications. Key results include the successful calibration of a single-gate GaN power device using TCAD simulations, which enabled us to accurately replicate the structural and operational characteristics of existing GaN devices.

Our optimized bi-directional HEMT structure achieved a favorable balance between breakdown voltage and specific on-resistance. By carefully tuning parameters such as gate-to-gate distance and field plate length, we minimized switching losses and improved electric field distribution, which are critical for stable and efficient power conversion.

Review and reflections

Initially, I chose this project due to my curiosity about the potential of GaN technology in power electronics and a desire to gain hands-on experience with advanced semiconductor design. This research allowed me to engage with technical concepts beyond standard coursework, such as TCAD simulations, device calibration, and the intricacies of high-voltage design, all of which have broadened my understanding of the field.

The project was challenging from the start, as I was new to GaN device. Under the guidance of Professor Wong and support from lab seniors, I received invaluable training that covered both theory and practical skills. This included learning the technical fundamentals of GaN-based devices, mastering the TCAD software, and understanding the intricacies of semiconductor structure. Throughout the project, I also read a wide range of research papers to gain a clearer picture of the current state and future direction of GaN technology, which strengthened my interest and understanding of power electronics. Each step in the project increased my appreciation for the rigorous process of device development and the innovation involved in solving complex engineering problems. This experience has inspired me to further pursue research in GaN technology and power electronics, as I see immense potential in this field for advancing high-efficiency power solutions.