Design of Trench Gate GaN Power MOSFET using Al₂O₃ Gate Oxide

Ey Goo Kang¹, Yong Tae Kim²

¹ Department of Photovoltaic Engineering, Far East University
Eumseong 369-700, Korea.
² Semiconductor Materials and Devices Laboratory, Korea Institute of Science and
Technology, Seoul 136-791, Korea

E-mail: ytkim@kist.re.kr

Abstract. A trench gate type 600V GaN power MOSFET structure with Al₂O₃ gate oxide has been
designed and simulated for obtaining optimum device and process parameters for fabrication. As a result,
when the trench gate depth is 2.4 μm, the breakdown voltage is 620V and the on resistance is 0.4Ωcm²,
which is relatively very low on resistance comparing with the same trench gate Si power MOSFET
structure.

1. Introduction
Recently, as a key component of power conversion and control devices in the power electronic
industry of high voltage, multi-functions and large capacity rising as one of the most attracting fields
in the electric and electronic industry, the power semiconductor element has faced a chance for rapid
growth along with the development of a power bipolar transistor and is popularly used as thyristor,
power MOSFET, IGBT (Insulated Gate Bipolar Transistor), MCT (MOS Controlled Thyristor), and
SIT (Static Induction Thyristor), etc.[1-2]

Practically, these power semiconductor devices are expected to be useful for the systematization of
the express subway and electric car in transportation fields, the FACTS (Flexible AC Transmission
System), HVDC (High Voltage DC) transmission and missile related equipment system in power fields,
and the design, fabrication, etc. of a micro-airplane, a military information system, as well as the
existing home appliances and industrial equipment.[3-5]

Meanwhile, since large capacity, chip size and durability of power chip are seriously concerned for
the above mentioned applications, compound power semiconductors such as GaN and SiC are newly
demanded. The compound power semiconductor takes advantage of a wide band gap and seems to be
the next generation power element due to its far more excellent thermal properties and on resistance
properties than the existing Si. However, considering that it is very hard to prepare a p type deep
junction (pillar structure) in GaN and SiC it is very important to suggest a method to avoid the
formation of p type deep junction.

Therefore, this work has proposed a structure of GaN power MOSFET, which is operated as a
normally off FET, and designed Al₂O₃ gate insulator instead of the SiO₂ gate dielectric layer by
considering the surface condition of GaN. Particularly, in this work, we have tried to investigate
effects of trench type gate on the optimal electrical performance of GaN power device to avoid p type junction doping that is known as a very hard process in the GaN.

Experiment Method

The proposed device structure is shown in Fig. 1. In this structure, N drift and P base layers are consisted on a N type GaN substrate to avoid the formation of P junction as mentioned in the introduction and a vertical channel is suggested by preparing the trench gate MOSFET structure.

Initially, the thickness of a gate oxide film is fixed as 0.1 \( \mu \text{m} \), the concentration and thickness of a N+ source are \( 3 \times 10^{18} \text{cm}^{-3} \) and 0.5 \( \mu \text{m} \), respectively. These values are given as the fixed conditions for the GaN power MOSFET operated as a normally off FET. The simulation was carried out by 2D simulation method using Athena and Atlas, Silvaco. From the proposed structure and the general relationship between a depletion layer and impurity concentration, optimal design and process parameters should be simulated for targeting about 600 V breakdown voltage. At first, the electric field applied to the N drift layer is calculated with the concentration of the N drift layer, predicting the critical electric field is 3.3 MV/cm as shown in Fig. 2. Based on this calculation, when the concentration of the N drift layer is \( 5 \times 10^{16} \text{cm}^{-3} \) the electric field applied to the N drift layer is reliable since it is less than the maximum critical electric field of 3.3 MV/cm. And, the relation between the thickness and the concentration of N drift layer reveals that the thickness of the N drift layer is 3.0 \( \mu \text{m} \).

![Figure 1](image_url). The proposed structure of a trench gate and Al₂O₃ gate oxide GaN power MOSFET
Figure 2. The relation between N-drift concentration and critical electrical field

Figure 3. The relation between N-drift concentration and N-drift Thickness

at the optimum concentration. However, to realize a trench gate structure it is necessary to adjust the thickness of the P base layer with the N drift layer. In this work, the thickness of the P base layer is changed from 1.5, 1.75, and 2 μm, respectively and then, the thickness of the N drift layer is simulated as shown in Fig. 3. Therefore, the thickness of the N drift layer is fixed at 2 μm as an optimal design parameter by considering the relation between the electric field and the concentration of a trench gate. As a result, the target breakdown voltage is 690V and Fig. 4 shows clearly how the thickness
variations of the P base and N drift layers are influenced on the breakdown voltage. Finally, the surrounding design and process parameters are optimized as presented in Table 1.

![Figure 4](image)

**Figure 4.** The characteristics of breakdown voltage according to the thickness of N drift and P base layers

| Division                | Concentration($\text{cm}^{-3}$) | Thickness ($\mu\text{m}$) |
|-------------------------|---------------------------------|---------------------------|
| gate depth              | -                               | 1.5                       |
| Gate oxide film         | -                               | 0.1, 0.2, 0.3             |
| p base                  | $1 \times 10^{17}$              | 1.75                      |
| n+ source               | $3 \times 10^{18}$              | 0.5                       |
| n drift                 | $5 \times 10^{16}$              | 2.0, 3.0                  |
| n+ substrate            | $3 \times 10^{18}$              | 150                       |

**Table 1.** Design and process parameter of simulation conditions.
2. Result and Consideration

Table 2. The electrical characteristics according to gate oxide thickness.

| Oxide Thickness | 0.1um | 0.2um | 0.3um |
|-----------------|-------|-------|-------|
| N-drift Thickness | Vth | BV | Vth | BV | Vth | BV |
| 2um | 3.5V | 570V | 7V | 620v | 11v | 700V |
| 3um | 3.5V | 640V | 7v | 680v | 11v | 790V |

As a device parameter, it is important to obtain threshold and breakdown voltage depending on the variations of Al₂O₃ gate thickness and N drift layer. Table 2 summarized the obtained results. As shown in the table, when the thickness of a gate oxide film is 0.2 μm and the thickness of the N drift layer is 2.0 μm, the breakdown voltage is 620V, which is increased to 680V that is still less than the target voltage at the N drift layer of 3.0 μm. However the threshold voltage is not changed and fixed at 7V constantly. Increasing the gate oxide thickness, the threshold and breakdown voltages rise up to 11 and 700V even at the optimum N drift layer.

Figure 5. The electrical characteristics according to the trench gate depth

It is important to understand how the breakdown voltage and the on resistance change with the trench gate depth. As shown in Fig.5, when the trench depth is 2.3 μm, the breakdown voltage is 660V, and the on resistance is 3 Ωcm². However, when the trench depth is 2.4 μm, the breakdown voltage is slightly decreased to 620V and the on resistance is abruptly decreased to 0.4Ωcm², which is a very low on resistance comparing with the same trench gate Si power MOSFET structure. This result suggests that the optimum trench depth in the proposed device structure is 2.4 μm. Comparing the effect of gate oxide material on the threshold voltage, Fig. 6 and 7 are the simulated results showing that the threshold voltage depends on the both materials, SiO₂ and Al₂O₃. Using the Al₂O₃ gate oxide, the threshold voltage reduces from 10 V, which is the threshold voltage of SiO₂ gate oxide case, to 7V.
Since both cases are operated with a normally off type and then, the Al$_2$O$_3$ gate oxide case indicates that the device is fast turned on. Finally, we can simulated the I-V characteristics of a trench gate and Al$_2$O$_3$ gate oxide GaN power MOSFET using the optimized parameters and 150 $\mu$m thickness of a GaN substrate. Fig.8 shows that when Vgs is 15V, the on resistance is 0.45m$\Omega$cm$^2$. If the Vgs increases from 5 to 15V, the average on resistance becomes to be slightly decreased to 0.4m$\Omega$cm$^2$.

![Figure 6](image_url)  
**Figure 6.** The characteristic of threshold voltage depending on 0.1 $\mu$m SiO$_2$ gate oxide

![Figure 7](image_url)  
**Figure 7.** The characteristic of threshold voltage depending on 0.2 $\mu$m Al$_2$O$_3$ gate oxide
Figure 8. The I-V characteristics of a trench gate and Al₂O₃ gate oxide GaN power MOSFET

Fig.9 shows the characteristic of breakdown voltage, which is one of the most important properties of a power semiconductor. Using the same optimum design parameters, it is found that the breakdown voltage is 620V, which is suitable for the application of 600V breakdown range.

Figure 9. The breakdown characteristic of a trench gate and Al₂O₃ gate oxide GaN Power MOSFET
3. Conclusion

We have proposed a trench gate type GaN power MOSFET that is operated by normally off type and tried to optimize design and process parameters targeting at the application of 600V class inverters. Especially, using Al₂O₃ as a gate oxide layer, the electrical characteristics such as the I-V characteristics, the on resistance, and the breakdown voltage are simulated. As a result, it is found that the breakdown voltage is 620V and the on resistance is $0.4\Omega \cdot \text{cm}^2$. This work will suggest a method to avoid the formation of p junction in the GaN power MOSFET structure, and the optimum parameters are also very useful to implement the GaN power switch element of 600V class, which has a great demand for green technology, so called electric cars, system connection, and inverters.

4. References

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