GaN (on Si)-Based High Voltage and High Switching Frequency Lateral Power Semiconductor Device

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Abstract—In the present work, a theoretical physics-based simulation study is carried out to know the breakdown strength and switching parameters of a GaN(on Si)-based optically triggered (latch free) lateral power semiconductor device. It is observed from the simulation study that the device can block up to 1500 V with the current handling capacity of 15 A. The device has turn-on and turn-off delays of 20 ns and 170 ns respectively, when triggered by an UV light source of 350 nm wavelength.

Index Terms—GaN, high voltage power electronics, lateral device structure, optical triggering, Si

I. INTRODUCTION

The emerging semiconductor material GaN has great potential for high voltage power electronics and high-temperature applications because of its attractive material properties such as wide bandgap energy (~ 3.44 eV), high electric breakdown field strength (~ 3.5 MV/cm), and high thermal conductivity (~1.3 W/cm.0K). A detailed comparison of the material properties of GaN with other existing semiconductor materials can be found in [1]-[4]. Recently, the author has proposed a vertical NPN device structure based on GaN/(4H)SiC heterojunction concept where it is observed that the turn-on and turn-off delays are quite large [5]. The reason can be attributed to the fact that the carrier life time in (4H)SiC is in the order of micro sec. whereas it is in the order of nano sec. in case of GaN. The only inconvenience associated with GaN material is the availability of large size wafer (maximum available wafer size: 3 inch) because of the requirements of extreme growth conditions and high melting point in comparison to other semiconductor materials’ growth conditions. To overcome this problem, epitaxial growth of GaN over various substrates such as Si, GaAs, (4H)SiC, and LiGaO2 have been tried [6]. amongst all these substrates, Si is the most economic and also large size Si wafers up to 6 inch are available in the market. However, the problem associated with Si substrate is the lattice mismatch of 16.9% resulting in high dislocation density. Also, the very high thermal expansion coefficient mismatch with GaN leads to high tensile stress resulting in crack formation in GaN epilayer. All these factors can affect GaN/Si device performance severely.

To alleviate these issues, in this work, a power device structure is proposed where a layer of AlN is placed over Si and then the GaN layers are placed over AlN which has a lattice mismatch of 2.5 % with GaN and is thermally robust. The electrical conduction in the device is made to be lateral by placing two electrodes on GaN material. One of the issues in the field of power electronics is the noise due to the electro-magnetic interference (EMI) which interferes the link between controlling switch and high voltage power stage and hence significantly affects the efficiency of the power converter. Thus, if the controlling switch is triggered by optical means, EMI immunity between the controller and the high voltage power stage is realized and also a complete electrical isolation is ensured. GaN material has very high optical absorption coefficient and is very much optically efficient in comparison to other materials. Therefore, keeping in view of all the above factors, in this work, a physics based simulation study with the help of semiconductor device simulation software packages ATLAS/MixedMode from Silvaco Inc., is conducted for the GaN (on Si)-based optically triggered (latch free) lateral power semiconductor device [7].

II. DEVICE STRUCTURE AND DESCRIPTION WITH RESULTS
The lateral semiconductor device structure which is simulated in ATLAS is shown in Fig. 1. The device contains two metal contacts; one at the left i.e., source contact and the other at the right i.e., drain contact (to be connected to a high voltage positive bias). The source and drain metal contacts consist of an alloy of Ti(150 Å)/Al(600 Å)/Re(200 Å)/Au (500 Å). N⁺-GaN regions (Region I) below the source and drain contacts are heavily doped to ensure ohmic contacts. This type of lateral arrangement also avoids any P-type metal contacts which is a very difficult task for GaN material. Because the technology for heavy P-type doping in GaN is still immature, the P⁺ GaN regions (Regions IV and II) below and above N⁺ GaN region (Region III), helps in forming the depletion regions and hence in blocking high voltage in the OFF-state of the device. Another advantage of P⁺ region (Region IV) is that it not only helps in blocking high voltage, but also ensures a latch free action i.e., complete turn-off of the device in the OFF-state unlike in conventional thyristor. The ON and OFF-state of the device is controlled by exciting it using the 350 nm UV pulsed light source. The low doped N⁻-GaN (Region I) = 1 x 10¹⁹/cm³, Region II doping = 1 x 10¹⁸ /cm³, Region III doping = 1 x 10¹⁵ /cm³, Region IV doping = 1 x 10¹⁸ /cm³, Region V doping = Undoped, Region VI doping = Undoped. Source thickness and length = 0.5 μm and 2.0 μm, Drain thickness and length = 0.5 μm and 5.0 μm, Region II thickness and length = 0.5 μm and 6.5 μm, Region III thickness and length = 2.0 μm and 20.0 μm, Region IV thickness and length = 4.0 μm and 20.0 μm, Region V thickness and length = 3.0 μm and 20.0 μm, External load = 10 ohm, Z dimension = 1 x 10⁹ μm, and light intensity = 100 W/cm².

Table 1. [SOURCE AND DRAIN DOPINGS (REGION I) = 1 x 10¹⁹ /cm³, REGION II DOPING = 1 x 10¹⁸ /cm³, REGION III DOPING = 1 x 10¹⁵ /cm³, REGION IV DOPING = 1 x 10¹⁸ /cm³, REGION V DOPING = UNDOPED, REGION VI DOPING = UNDOPED, SOURCE THICKNESS AND LENGTH = 0.5 μm AND 2.0 μm, DRAIN THICKNESS AND LENGTH = 0.5 μm AND 5.0 μm, REGION II THICKNESS AND LENGTH = 0.5 μm AND 6.5 μm, REGION III THICKNESS AND LENGTH = 2.0 μm AND 20.0 μm, REGION IV THICKNESS AND LENGTH = 4.0 μm AND 20.0 μm, REGION V THICKNESS AND LENGTH = 3.0 μm AND 20.0 μm, EXTERNAL LOAD = 10 ohm, Z DIMENSION = 1 x 10⁹ μm, AND LIGHT INTENSITY = 100 W/cm², SWITCHING FREQUENCY = 200 KHZ, AND DUTY CYCLE = 40 %]

<table>
<thead>
<tr>
<th>Device structure</th>
<th>Breakdown Voltage (V)</th>
<th>Turn-on delay (ns)</th>
<th>Turn-off delay (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaN(on Si)-lateral device</td>
<td>1500</td>
<td>20</td>
<td>170</td>
</tr>
</tbody>
</table>

![Device Structure Diagram](image)

**Figure 1.** GaN (on Si)-based optically triggered lateral power semiconductor device.

Fig. 2(a) shows the voltage blocking characteristics of the device. We can see the device can block up to 1500 V before the leakage current starts to increase. This high blocking capacity of the device can be attributed to the fact that GaN material has very high electrical breakdown strength. Fig. 2(b) shows the transient characteristics of the device. The device has a current of 15 A when subjected to an input optical pulse of 100 W/cm² with a switching frequency of 200 KHz and 40 % of duty cycle. The turn-on and turn-off delays of the device are 20 ns and 170 ns respectively. The fast transient response of the device is due to the fact that GaN material has very fast carrier life time and high recombination coefficient.
III. CONCLUSION

In the present work, a physics based simulation is conducted for the GaN (on Si)-based optically triggered (latch free) power semiconductor device. From the simulation results, it is observed that the proposed device can block up to 1500 V in the OFF-state with a fast transient response having turn-on delay of 20 ns and turn-off delay 170 ns and these parameters are highly suitable for high voltage power electronics applications. The proposed device structure is scalable for high voltage and high current handling capacity.

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REFERENCES


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M. Chukhman is a Research Programmer in the Department of Bioengineering, University of Illinois at Chicago, Chicago, Illinois, USA. He has specialties in various programming languages such as C/C++, Java, VS etc. and operating systems like Linux, Unix, and Windows. He has also expertise in the maintenance of high performance of supercomputers and clusters.