CHAPTER 4

SIMULATION OF SINGLE LAYER GaN CHANNEL THIN FILM TRANSISTOR
4.1 Introduction

Gallium nitride has been considered as one of the most capable compound semiconductor in past decade. GaN based high-electron mobility transistors has been the focus of intense research activities in the area of high power, high-speed, and high-temperature transistors. This chapter presents a design and simulation of the GaN based thin film transistor using Sentaurus TCAD for extracting the electrical performance of the device. As a result, GaN thin film transistor exhibits good electrical performance in the simulation including a threshold voltage of 12-15 V, an \( I_{\text{ON}}/I_{\text{OFF}} \) ratio of \( 6.5 \times 10^7 \sim 8.3 \times 10^8 \), and a subthreshold slope of 0.44V/decade. Sentaurus TCAD simulations tool enables the study of comprehensive behavior of semiconductor structures. The simulation results of the presented TFT based on gallium nitride as an active channel shows its great perspective in the next-generation flat-panel display applications.

4.2 Material Properties of GaN

Silicon (Si) and Germanium (Ge) are group IV elements in the periodic table. Gallium (Ga), Indium (In), Aluminum (Al) are all group III elements. Nitrogen (N), Arsenic (As), Antimony (Sb), Phosphorus (P) are all group V elements. By combining group III elements with group V elements, III-V compound semiconductors can be formed. The electron configuration of Gallium Nitride (GaN) is [Ar] \( 4s^24p^1 \) for Gallium (Ga) and [He] \( 2s^22p^3 \) for Nitrogen (N). By sharing 4p and 2p electrons through the covalent bond, the compound Gallium Nitride (GaN) is formed. Also other III-V compound semiconductors such as GaAs and InP can be formed in the same way. In Table 4.1 bulk material properties are summarized for Si, GaAs, GaN and InSb [Ma (1997)]. It can be seen from Table 4.1 that
GaN has superior transport properties for high temperature and high power applications when compared to the other material [Smith and Davis (1994)].

Table 4.1 Material Properties of Si, GaAs, GaN, 4H-SiC and InSb

<table>
<thead>
<tr>
<th></th>
<th>Silicon</th>
<th>GaAs</th>
<th>GaN</th>
<th>4H-SiC</th>
<th>InSb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap energy (E_g eV)</td>
<td>1.12</td>
<td>1.42</td>
<td>3.41</td>
<td>3.26</td>
<td>0.17</td>
</tr>
<tr>
<td>Dielectric constant (ε_r)</td>
<td>11.8</td>
<td>12.8</td>
<td>9</td>
<td>9.7</td>
<td>17.7</td>
</tr>
<tr>
<td>Thermal conductivity (k_\text{th} W/cm°K)</td>
<td>1.5</td>
<td>0.46</td>
<td>1.3</td>
<td>3.7</td>
<td>0.18</td>
</tr>
<tr>
<td>Breakdown field (E_B V/cm)</td>
<td>3×10^5</td>
<td>5×10^5</td>
<td>3.3×10^6</td>
<td>3×10^6</td>
<td>1×10^3</td>
</tr>
<tr>
<td>Saturation velocity (v_{\text{sat}} cm/s)</td>
<td>1×10^7</td>
<td>2×10^7</td>
<td>3×10^7</td>
<td>2×10^7</td>
<td>6×10^7</td>
</tr>
<tr>
<td>Electron mobility (μ_e cm^2/V.s)</td>
<td>1350</td>
<td>8500</td>
<td>1200</td>
<td>900</td>
<td>7800</td>
</tr>
<tr>
<td>Hole mobility (μ_h cm^2/V.s)</td>
<td>450</td>
<td>400</td>
<td>200</td>
<td>120</td>
<td>850</td>
</tr>
</tbody>
</table>

In many respects, ZnO is considered to be an alternative to GaN for device applications owing to its relatively low production cost and superior optical properties. Gallium nitride (GaN) is a high electron mobility (HEMT) semiconductor, Although GaN is young in its life cycle, but will certainly see significant improvements in the years to come [Yamamoto et al. (2012)]. GaN-based power field effect transistors (FETs) are capable of producing over 800 W of CW power in the communication band. The light-emitting diodes (LEDs) have created a large market for GaN emphasized to more efficient performance. On the electronic side, the relatively low mobility of ZnO as compared to GaN and nearly four times stronger electron–phonon coupling together with relatively low thermal conductivity are serious shortcomings for ZnO. Gallium Nitride has been in-use for high-electron mobility transistors, and are the focus of intense research activities in the area of high power, high-speed, and high-temperature transistors. The material features and current research interest for gallium nitride have drawn the attention to use GaN as a channel...
material in TFTs. Hence, Gallium Nitride material has been chosen for thin film transistor design and simulation.

4.3 Device Structure and Design

This chapter reports the simulation and results of a thin–film transistor using GaN as an active channel layer. The basic structure of the gallium nitride channel thin film transistor is shown in Figure 4.1. The TFT structure is generated using Sentaurus TCAD tool. The device is simulated to obtain the electrical characteristics. The electrical parameters i.e. threshold voltage, mobility and current on-off ratio are extracted to determine the functional behavior of the device.

![Figure 4.1 Illustration of TFT Structure with GaN as an active channel layer](image-url)

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Semiconductor manufacturers face the challenge of developing process technologies within strict time and cost constraints. TCAD reduces the number of engineering wafers, saving time and money. The GaN TFT with metallic source and drain are simulated using Sentaurus Structure Editor, Sentaurus Device and Inspect modules of Sentaurus TCAD. Sentaurus structure editor is used to design the TFT structure and appropriate meshing by intuitive meshing engine. The structure of the designed device is shown in Figure 4.3.

The simulated device structure includes a GaN channel layer, 150 nm thick Au source and drain regions and 100 nm thick SiO$_2$ gate dielectric region. The device has a gate length of 0.7 µm, source is 0.5 µm and drain is 1.0 µm away from the gate. SiO$_2$ gate dielectric region has a length of 2.2 µm from the source to the drain region. Sentaurus Device module simulates the electrical behavior of a semiconductor device. Contact potentials and the barrier height of the gate contact are defined in the Electrode section. Contact potentials for the source, drain and gate are defined as 0 Volts. Gate contact is also defined as Au by defining its work function 5.10 eV, in the Electrode section. Sentaurus Device allows different physical models to simulate semiconductor devices.

Mobility model, generation-recombination rate, material-dependent parameters, interface and contact boundary conditions are defined in the Physics section. The first model that is described in this section is the mobility model. In doped semiconductors, scattering of the carriers by charged impurity ions leads to degradation of the carrier mobility. The model for the mobility degradation due to impurity scattering is activated by specifying the ‘DopingDependence’ term in the Mobility section. In high electric fields, the carrier drift velocity is no longer proportional to the electric field, instead, the velocity saturates to a finite speed $v_{\text{sat}}$.

The high-field saturation models comprise three submodels: the actual mobility model, the velocity saturation model, and the driving force model. The driving force model is selected by the term ‘eHighFieldSaturation (CarrierTempDrive)’ in the Mobility section. The term CarrierTempDrive requires hydrodynamic simulation. Also, the default driving force model is chosen by specifying the term ‘hHighFieldSaturation (GradQuasiFermi)’. The second model that is defined in this section is the band gap model. The bandgap model is
selected by using the ‘EffectiveIntrinsicDensity’ statement in the Physics section. The third model that is defined in this section is the recombination model. For metal-semiconductor interfaces, by default, there is an ohmic boundary condition. Therefore, Au/GaN interface is defined as Schottky in the Physics Section using the syntax “ ” (MaterialInterface = “Au/GaN”) ‘eRecVelocity=2.357e6’ ‘hRecVelocity=1.93e6’. The default values for eRecVelocity and hRecVelocity are used. Figure 4.2 shows the defined strategy flow chart followed design of GaN TFT simulation work.

The term ‘Fermi’ is also defined in the Physics section due to simulating a heterostructure device. For high values of carrier densities, the Fermi (Fermi-Dirac) should be used to have appropriate results. Device performs an $I_{DS}-V_{DS}$ sweep with $V_{DS}$ values ranging from 0 V to +4 V at a fixed $V_{GS}$ of 5 V, followed by an $I_{DS}-V_{GS}$ sweep at $V_{DS}$ of 5 V and $V_{GS}$

Figure 4.2 The strategy flow chart
ranging from -3 V to 2 V. $I_{DS}$ versus $V_{DS}$ curve and $I_{DS}$ versus $V_{GS}$ curve were plotted by Inspect module.

### 4.4 Device Simulation

#### 4.4.1 Generation of Structure using Sentaurus TCAD

Two dimensional layout of the TFT was created using the structure editing tool. Figure 4.3 shows the single layer gallium nitride channel structure.

![Two dimensional Structure of of GaN active channel TFT for simulation using Sentaurus TCAD](image)

Figure. 4.3 Two dimensional Structure of of GaN active channel TFT for simulation using Sentaurus TCAD
Graphical user interface of structure editor open a window when the command is entered. The window has its three parts. Menubar, View window and Command-line window. Contacts are defined to allow the structured device to connect with the sources. The contacts name, sets, properties, edge color, thickness are defined for the structure.

### 4.4.2 Defining Doping in the Structure using Sentaurus TCAD

Doping is the process of introducing impurity concentration. TCAD allows to select analytical and constant doping profile. A concentration of $1 \times 10^{15}$, arsenic active concentration dopants are introduced by adding constant doping profile into the silicon to increase the mobility at the dielectric semiconductor interface. A constant boron background doping of $1 \times 10^{15}$ cm$^{-3}$ was appropriately incorporated into the silicon material by selecting placement name, material, species, and concentration field in the constant profile placement dialog box. The doping profile placement can be saved in .cmd as shown in Figure 4.5.

### 4.4.3 Meshing Strategy of the Structure and Generation of Mesh

Once the device is structured, contacts are set and doping profile has been selected, the next process of design is Meshing. Sentaurus Mesh is a modular 2D and 3D mesh generator that can create both axis-aligned and tensor meshes to be used in simulators. The meshing uses the box discretization or finite-difference time-domain (FDTD) methods for spatial device discretization. The generated mesh of the designed ZnO channel TFT is saved which can be viewed in Sentaurus Visual. Figure 4.6 show the output of the saved scheme in SVisual module. Generated grids can directly be loaded into Sentaurus Device and Sentaurus Process module. Depending on the mesh generator used,
Sentaurus Mesh produces different output formats. The axis-aligned mesh generator always produces a TDR unstructured mesh. In Sentaurus Structure Editor, the mesh generation process is performed in two steps. The first step defines the meshing strategy, which includes the maximum and minimum meshing step definition in each device dimensions as well as the mesh refinement strategies.

The second step links the defined strategy from the first step to a specific target, which is, in general, a material, or a device region, or a user-defined evaluation window. Note that different device regions have different roles in terms of determining the device performance, thereby the required meshing strategies for these regions are typically different. Figure 4.4 shows the meshing strategy adopted for the min-max element size and then build mesh was generated.

Figure. 4.4 Meshing Structure of bottom gate GaN channel TFT for simulation.
Figure 4.5 Meshing Structure and doping profile of bottom gate GaN channel TFT obtained using SMesh

Figure 4.6 Meshing Elements and Success of Build Mesh of the structure.
4.5 Simulation Results

After running simulation, the simulation results of step by step were saved. Drain and transfer characteristics of the device could be observed using Inpect module of the Sentaurus TCAD. From the obtained characteristics of the GaN based thin film transistor the electrical performance parameters were extracted and calculated. The volt-ampere characteristics and extracted electrical parameters are presented in this section.

4.5.1 Transfer Characteristics

The transfer characteristics between $V_{GS}$ and $I_D$ at keeping constant drain source voltage are shown in the Figure 4.7. A good approximation with experimental results of TFT can be seen.

![Figure 4.7 Simulated transfer characteristics for different values of drain to source bias.](image)

$I_{OFF} = 0.21427$
4.5.2 Drain Characteristics

Drain characteristics $V_{DS}$ vs $I_D$ at gate voltage constant at 7V-19 V are shown in Figure 4.8. Series1, 2 3 and 4 are corresponding to the constant values of $V_{GS}$ at 7V, 10V, 13V and 19V.

Figure. 4.8 Simulated drain characteristics for constant gate to source bias.
4.5.3 Electrical Performance Parameters

The resulting GaN TFTs shows suitable electrical performance in the simulated results, including, a threshold voltage of 12-15 V, an on/off current ratio of $6.5 \times 10^7 \sim 8.3 \times 10^8$, and a subthreshold slope of 0.44V/decade. Sentaurus TCAD simulations tool offers study of comprehensive behavior of semiconductor structures with ease.

Table 4.2 Threshold voltage, ON/OFF ratio, saturation mobility and sub–threshold slope values under different DOS values.

<table>
<thead>
<tr>
<th>Electrical Parameter</th>
<th>Density of States $(1 \times 10^{15})$ in cm$^{-3}$ eV$^{-1}$</th>
<th>Density of States $(1 \times 10^{18})$ in cm$^{-3}$ eV$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold Voltage (V)</td>
<td>~ 15</td>
<td>~ 12</td>
</tr>
<tr>
<td>ON current</td>
<td>$1.4 \times 10^7$</td>
<td>$2.5 \times 10^8$</td>
</tr>
<tr>
<td>Off current</td>
<td>0.21427</td>
<td>0.31224</td>
</tr>
<tr>
<td>ON/OFF ratio</td>
<td>$6.5 \times 10^7$</td>
<td>$8.3 \times 10^8$</td>
</tr>
<tr>
<td>Saturation Mobility</td>
<td>$3.36 \times 10^{-6}$</td>
<td>$6.97 \times 10^{-3}$</td>
</tr>
<tr>
<td>Sub-threshold slope(V/decade)</td>
<td>0.44</td>
<td>0.36</td>
</tr>
</tbody>
</table>

The electrical parameters are calculated from the values of drain current $I_{DS}$ in the saturation regime of the device. The parameter extraction has been discussed in Chapter 1. Table 4.2 shows the obtained electrical parameters at diverse density states.