Compact Modeling of HfO$_2$/SiC MOS Devices

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Introduction

Wide bandgap semiconductors are an important focus of research in the field of electronic devices. Such materials have unique physical properties that enable them to outperform traditional semiconductors like silicon in key situations, such as at high temperatures or under large applied voltages. Silicon carbide (SiC) is one such material, with a bandgap approximately three times larger than that of silicon.

Although the use of SiC has been maturing for several decades, more research is necessary to further develop its applications. This work explores the use of hafnium oxide (HfO$_2$) as a gate dielectric for SiC MOS capacitors. High-k-dielectrics like HfO$_2$ are desirable for use in MOS capacitors because they produce larger gate capacitances for a given dielectric thickness, thus enabling closer-to-ideal behavior in the subthreshold region of a given dielectric thickness. This work explores the use of hafnium oxide (HfO$_2$) as a gate dielectric for SiC MOS capacitors because they produce larger gate capacitances for a given dielectric thickness, thus enabling closer-to-ideal behavior in the subthreshold region of a given dielectric thickness.

Methodology

This SiO$_2$/Si MOS capacitor model, as well as a directly comparable model with source and drain implants and contacts added, is simulated to extract EKV parameters. Upon successful demonstration of this process, a HfO$_2$/SiC MOS capacitor is created and parameters are adjusted for successful SiC simulation.

Before the EKV parameters can be extracted from TCAD for further use, however, the simulation must be calibrated against a real fabricated device. HfO$_2$ was deposited on an n-type SiC wafer via thermal evaporation, and the thickness of the HfO$_2$, as measured to be 300Å via ellipsometry. Measurements of substrate doping, dielectric constant, fixed oxide charge, and threshold voltage were then made with a mercury probe at 2MHz, and these measurements were directly applied to the TCAD model to produce EKV parameters for the produced device. SiO$_2$/Si and HfO$_2$/Si MOS capacitors were additionally produced and measured.

After completing the experiments using the mercury probe and simulating the MOS capacitor in TCAD, the next step is to perform the analytic equations in Python. The parameters that were extracted were to create an EKV model of the MOSFET. The EKV model was chosen because it is the simplest model that includes subthreshold. The subthreshold region is important because when a transistor is below the threshold voltage, it does not fully turn off. After creating the EKV model, the next step is to create a SPICE model for the MOSFET.

To address the issue with the low carrier concentration of silicon carbide as compared to silicon at room temperature, the first step before designing the opamp using the gm/ID method is to make sure the offset voltage is at the minimum and with a reasonable output current and voltage. Using the gm/ID method and picking a bias current, values for gm were found for the NMOS and the PMOS. The next step is to find the resistance of the resistor to find the gain of both sides, and then multiply to find the linear gain. The parameters of gm and resistance are used to find gain because both parts are common source amplifiers.

After finding the DC gain, the next step is to stabilize the opamp by finding the gain bandwidth by adding a resistor and capacitor. The two ways that the opamp was tested was the buffer and integrator. The opamp design is displayed in Figure 2.

Finally, the frequency response of the HfO$_2$/SiC opamp with compensation, as seen in Figure 2, is displayed in Figure 4. This frequency response portrays a functioning, practical opamp.

Analysis and Results

Figure 3 displays capacitance-voltage curves for the fabricated HfO$_2$/Si MOS capacitors (as measured by the mercury probe) and the associated curves of the calibrated TCAD model. These curves show strong agreement, indicating the validity of the simulation environment.

Table 1: Extracted HfO$_2$/SiC EKV parameters

<table>
<thead>
<tr>
<th>Type</th>
<th>VTO [V]</th>
<th>GAMMA [V$^{-1}$]</th>
<th>PSI [V]</th>
<th>K</th>
<th>[A/V$^2$]</th>
<th>LAMBDAM [a/V$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NMOS</td>
<td>1</td>
<td>1.43</td>
<td>1.45</td>
<td>1.83</td>
<td>2.5</td>
<td></td>
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<tr>
<td>PMOS</td>
<td>-1</td>
<td>0.45</td>
<td>1.5</td>
<td>0.83</td>
<td>2.5</td>
<td></td>
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</tbody>
</table>

Summary/Conclusions

This project successfully demonstrates a process for the compact modeling of HfO$_2$/SiC devices. Using a TCAD model calibrated to a fabricated device, the EKV parameters of a HfO$_2$/SiC MOS capacitor were extracted, thus enabling the design of analog applications such as an operational amplifier. The results of operational amplifier simulation further demonstrate that this process produces functioning realistic designs. Ultimately, this flow may be utilized for future design with HfO$_2$/SiC-based devices.

Key References


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