Characterization of Interface State in Silicon Carbide Metal Oxide Semiconductor Capacitors

by

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ABSTRACT

Silicon carbide (SiC) has always been considered as an excellent material for high temperature and high power devices. Since SiC is the only compound semiconductor whose native oxide is silicon dioxide (SiO₂), it puts SiC in a unique position. Although SiC metal oxide semiconductor (MOS) technology has made significant progress in recent years, there are still a number of issues to be overcome before more commercial SiC devices can enter the market. The prevailing issues surrounding SiC MOSFET devices are the low channel mobility, the low quality of the oxide layer and the high interface state density at the SiC/SiO₂ interface. Consequently, there is a need for research to be performed in order to have a better understanding of the factors causing the poor SiC/SiO₂ interface properties.

In this work, we investigated the generation lifetime in SiC materials by using the pulsed metal oxide semiconductor (MOS) capacitor method and measured the interface state density distribution at the SiC/SiO₂ interface by using the conductance measurement and the high-low frequency capacitance technique. These measurement techniques have been performed on n-type and p-type SiC MOS capacitors. In the course of our investigation, we observed ‘fast interface states’ at semiconductor-dielectric interfaces in SiC MOS capacitors that underwent three different interface passivation processes, such states were detected in the nitrided samples but not observed in PSG-passivated samples. This result indicates that the lack of fast states at PSG-passivated interface is one of the main reasons for higher channel mobility in PSG MOSFETs. In addition, the effect of mobile ions in the oxide on the response time of interface states has been investigated. In the last chapter we propose additional methods of investigation that can help elucidate the
origin of the particular interface states, enabling a more complete understanding of the SiC/SiO₂ material system.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>LIST OF TABLES</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>v</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>LIST OF FIGURES</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>vi</td>
</tr>
</tbody>
</table>

## CHAPTER

1. INTRODUCTION ................................................................. 1
   1.1. Silicon Carbide ....................................................... 1
   1.2. Polytypism ............................................................ 2
   1.3. Physical Properties ................................................ 6
   1.4. Silicon Carbide applications ....................................... 7

2. CARRIER LIFETIMES IN 4H-SiC MOS CAPACITORS ....................... 10
   2.1. Introduction .......................................................... 10
   2.2. The Pulsed SiC MOS Capacitor ..................................... 11
   2.3. Experimental Details, Results and Discussion .................... 16

3. INTERFACE PASSIVATION FOR SILICON DIOXIDE LAYERS ON SILICON CARBIDE ......................................................... 20
   3.1. Introduction .......................................................... 20
   3.2. Nitrogen Passivation Annealing .................................... 20
   3.3. Phosphorus-Doped Gate Oxide ....................................... 23
   3.1. Nitrogen Plasma Annealing .......................................... 25
<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. INTERFACE STATES AT the SiC/SiO\textsubscript{2} INTERFACE</td>
<td>27</td>
</tr>
<tr>
<td>4.1. Interface State</td>
<td>27</td>
</tr>
<tr>
<td>4.2. Conductance Measurement</td>
<td>36</td>
</tr>
<tr>
<td>4.3. High-Low Frequency Capacitance Method</td>
<td>45</td>
</tr>
<tr>
<td>4.4. Conductance Measurement of SiC MOS-C</td>
<td>51</td>
</tr>
<tr>
<td>4.5. High-Low Frequency Capacitance Method on SiC MOS-C</td>
<td>66</td>
</tr>
<tr>
<td>5. FAST INTERFACE STATES IN NITROGEN- AND PHOSPHORUS TREATED 4H-SIC MOS CAPACITORS</td>
<td>70</td>
</tr>
<tr>
<td>5.1. Fast Interface States</td>
<td>70</td>
</tr>
<tr>
<td>5.2. Response Time of Interface States in Wide Bandgap Semiconductor</td>
<td>72</td>
</tr>
<tr>
<td>5.3. Measurements of Fast Interface States</td>
<td>75</td>
</tr>
<tr>
<td>5.4 Conclusion</td>
<td>88</td>
</tr>
<tr>
<td>6. FUTURE WORK</td>
<td>89</td>
</tr>
<tr>
<td>6.1. Future Work</td>
<td>89</td>
</tr>
<tr>
<td>6.2. Deep-Level Transient Spectroscopy</td>
<td>91</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>100</td>
</tr>
<tr>
<td>Table</td>
<td>Page</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1.1. Important Material Properties of 3C-SiC, 4HSiC and 6HSiC Polytype</td>
<td>5</td>
</tr>
<tr>
<td>1.2. Properties of Common Polytypes of SiC Compared with Si, GaAs, and GaN</td>
<td>6</td>
</tr>
<tr>
<td>4.1. Parameters for the Various Semiconductors – Bandgap, Electron Affinity (EA) and Charge-Neutrality level (CNL)</td>
<td>35</td>
</tr>
<tr>
<td>4.2. Basic Sample Information Used for This Research</td>
<td>51</td>
</tr>
<tr>
<td>4.3. Oxide Charge Behavior Before and After BTS</td>
<td>59</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1.</td>
<td>The Characteristic Tetrahedron Building Block of SiC Crystal. Four Carbon Atoms are Covalently Bonded with a Silicon Atom in the Center</td>
<td>2</td>
</tr>
<tr>
<td>1.2.</td>
<td>Si-C-Bilayer</td>
<td>3</td>
</tr>
<tr>
<td>1.3.</td>
<td>Close Packed Spheres to Visualize SiC Stacking Sequence</td>
<td>4</td>
</tr>
<tr>
<td>1.4.</td>
<td>Comparison of Intrinsic Carrier Concentration Versus Temperature for Si, 4H-SiC, 4H-SiC, and GaN</td>
<td>8</td>
</tr>
<tr>
<td>2.1.</td>
<td>Plot of (a) Gate Voltage Versus Time, (b) Capacitance Versus Gate Voltage and (c) Capacitance Versus Time</td>
<td>11</td>
</tr>
<tr>
<td>2.2.</td>
<td>Generation Components Described in the Text Which Contribute to the Recovery of the Pulsed MOS-C Depicted (A) on a Band Diagram and (B) in the Device</td>
<td>13</td>
</tr>
<tr>
<td>2.3.</td>
<td>(a) Typical C-t Transients During Inversion Layer Formation and (b) the Resulting Zerbst Plot</td>
<td>15</td>
</tr>
<tr>
<td>2.4.</td>
<td>C-t Response for (a) n-type and (b) p-type SiC MOS-C in Deep Depletion at 400°C</td>
<td>17</td>
</tr>
<tr>
<td>2.5.</td>
<td>Comparison of C-V Curves for (a) n-type and (b) p-type SiC MOS-C Before and After Annealing. T=400°C</td>
<td>18</td>
</tr>
<tr>
<td>2.6.</td>
<td>C-t Response for p-type SiC MOS-C After Heated Up to 400°C and Cooled Down to Room Temperature 3 Times</td>
<td>19</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>3.1. Interface Trap Density in the Upper 4H-SiC Bandgap for Unpassivated Samples and Sample Passivated with NO and NO+H₂</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td>3.2. Field-Effect Mobility Before and After Passivation for Lateral MOSFETs</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>3.3. Interface Trap Density in the Upper 4H-SiC Bandgap for Unpassivated Samples, NO Passivated Samples and PSG Passivated Samples under Different Passivation Temperature</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>3.4. Field-Effect Mobility for Unpassivated Samples, NO Passivated Samples and PSG Passivated Samples</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>4.1. Charges and Their Locations in an Oxide/Semiconductor Cross Sections</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>4.2. Energy-Band Diagram of a MOS Structure, Depicting the distribution of Interface States in the Bandgap of the Semiconductor at the Oxide/Semiconductor Interface</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>4.3. General Interface States System Consisting of Both Donor and Acceptor States. This is Often Expressed by an Equivalent Distribution with a Charge-Neutrality Level E_{CNL} above which the States are Acceptor Type and Below Which They are Donor Type. When E_F is Above (Below) E_{CNL}, Net Charge is – (+)</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>4.4. (a) (b) Equivalent Circuits Including Interface State Effects, C_{it} and R_{it} [39]. (c) Low-Frequency Limit. (d) High-Frequency Limit</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>4.5. Equivalent Circuits for Conductance Method; (a) Standard MOS Capacitor, (b) Simplified Circuit of (a), (c) Measured Circuit, (d) including series resistance r_s and Tunnel Conductance G_t and (e) Admittance Circuit</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>4.6. G_P/ω Versus ω in Under Different Bias Measured on a Silicon MOS Capacitor</td>
<td>39</td>
<td></td>
</tr>
</tbody>
</table>
4.7. \( G_p/\omega \) Versus \( \omega \) for Experimental Data Measured from Si/SiO\(_2\) Interface, Single Level [Equation (4.10)] and Continuum [Equation (4.11)]. For all Curves: 
\[ D_{it}=1.9 \times 10^9 \text{cm}^{-2}\text{eV}^{-1}, \quad \tau_{it}=7 \times 10^{-5} \text{s} \] ............................................................................41

4.8. Interface Trap Density \( D_{it} \) versus Energy for Quaasi-Static and Conductance Method on (a) (111) n-Si and (b) (100) n-Si ...............................................................42

4.9. Capacitance Measured on Silicon MOS Capacitor at High and Low Frequency .49

4.10. \( D_{it} \) Profile Measured Using High-Low Frequency Method on Silicon MOS Capacitor ........................................................................................................50

4.11. Small Signal ac Interface State Conductance \( G_p/\omega \) as a Function of \( \omega \) on (a) P5L01 and (b) P5L04 at Room Temperature .................................................................52

4.12. Interface Trap Capture Cross-Section vs Energy for P5L05 ..................................................53

4.13. Small Signal ac Interface State Conductance \( G_p/\omega \) as a Function of \( \omega \) on P5L04 (a) Before and (b) After Moving The Ions Close To The Interface ..................54

4.14. (a) Extracted \( D_{it} \) Profile and (b) Energy Range at Different Conditions on P5 Sample ..................................................................................................................55

4.15. Small Signal ac Interface State Conductance \( G_p/\omega \) as a Function of \( \omega \) on Cree1-3L04 After Moving the Ions (a) Away From and (b) Close to the Interface ..56

4.16. (a) Extracted \( D_{it} \) Profile and (b) Energy Range at Different Conditions on Cree1 sample ..................................................................................................................57

4.17 C-V Curve Measured by Sweeping Towards Different Directions on (a) Cree1, (b) NO0219, (c) PSG0225 and (d) Cree 2 ....................................................................................58
4.18. C-V after BTS for (a) NO0219-12 and (b) PSG0225-12……………………59
4.19. Small Signal ac Interface State Conductance \(G_p/\omega\) as a Function of \(\omega\) on NO0219-12 Before and After BTS at \(\phi_s \approx 0.09eV\)………………………………60
4.20. (a) Small Signal ac Interface State Conductance \(G_p/\omega\) as a Function of \(\omega\) in the Depletion Region on and (b) Extracted \(D_{it}\) Profile for NO0219……………………..61
4.21. (a) Small Signal ac Interface State Conductance \(G_p/\omega\) as a Function of \(\omega\) and (b) Extracted \(D_{it}\) Profile for Cree3………………………………………………………62
4.22. (a) Small Signal ac Interface State Conductance \(G_p/\omega\) as a Function of \(\omega\) at \(\phi_s=0.09\) and (b) Extracted \(D_{it}\) Profile with and without Parasitic Reduction for NO0219………………………………………………………………………………63
4.23. Small Signal ac Interface State Conductance \(G_p/\omega\) as a Function of \(\omega\) Scale to (a) Low Frequency Peak, (b) High Frequency Peak for PSG225…………………..63
4.24. Extracted \(D_{it}\) Profile for PSG225……………………………………………………64
4.25. (a) Small Signal ac Interface State Conductance \(G_p/\omega\) as a Function of \(\omega\) and (b) Extracted \(D_{it}\) Profile for 145…………………………………………………………65
4.26. Interface Trapped Charge Density versus Energy from the High-Low Frequency and Conductance Capacitance Measurement on NO0219…………………………………67
4.27. Interface Trapped Charge Density versus Energy from the High-Low Frequency and Conductance Capacitance Measurement on PSG225……………………………………..68
4.28 Interface Trapped Charge Density versus Energy from the High-Low Frequency and Conductance Capacitance Measurement on 145……………………………………..69
<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1. Time Constant for Holes to Emit from an Interface State to the Valence Band in a p-Type 4H-Sic. Capture Cross Section for Holes in (10^{15}) (\text{cm}^2). The Horizontal Lines Indicate the Frequency Limitation of the Agilent 4294 Impedance Meter.</td>
<td>72</td>
</tr>
<tr>
<td>5.2. The Conductance (G_p/\omega) versus (\omega) at 220 K, 180 K, 140 K and 100 K Measured on NO Passivated Sample</td>
<td>78</td>
</tr>
<tr>
<td>5.3. The Conductance (G_p/\omega) versus (\omega) at 220 K, 180 K, 140 K and 100 K Measured on N-plasma Passivated Sample</td>
<td>79</td>
</tr>
<tr>
<td>5.4. Interface State Density for NO and N-plasma Sample Extracted from the Curves in Figs. 5.2 and 5.3</td>
<td>80</td>
</tr>
<tr>
<td>5.5. The Conductance (G_p/\omega) versus (\omega) at Room Temperature Measured on Sample (a) PSG11 and (b) PSG 12</td>
<td>81</td>
</tr>
<tr>
<td>5.6. Observed Interface State Density for (a) NO, (b) N-plasma, (c) PSG11 and (d) PSG12 Sample Extracted from the Conductance Method and the High-Low Capacitance Method</td>
<td>83</td>
</tr>
<tr>
<td>5.7. Comparison of Observed Interface State Density for NO, N-plasma, PSG11 and PSG12 Samples Extracted by High-Low Frequency Capacitance Measurement at 300 K</td>
<td>86</td>
</tr>
<tr>
<td>5.8. Capture Cross-Section for Fast Interface States in NO and N-plasma Samples and Regular States in PSG Samples</td>
<td>87</td>
</tr>
<tr>
<td>6.1. Capacitance versus Time at Different Temperature. (t_1) and (t_2) Are the Sampling Time</td>
<td>91</td>
</tr>
<tr>
<td>Figure</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>6.2. DLTS Spectra for Fixed $t_2/t_1$ and Different $t_1$ and $t_2$</td>
<td>94</td>
</tr>
<tr>
<td>6.3. n-Substrate MOS Capacitor Band Diagram with (a) No Bias, (b) Positive Bias and (c) Negative Bias</td>
<td>96</td>
</tr>
</tbody>
</table>
1.1. Silicon Carbide

In the past four decades, logic transistor scaling following Moore’s Law has resulted in unprecedented in logic performance, with devices becoming smaller, faster and much more complicated over the years [1]. While the silicon transistor is getting close to its physical scaling limit, part of the industry’s focus has been shifting towards making better high-temperature and high-power devices. For high-temperature and high-power devices, SiC is the leading contender among other wide bandgap semiconductors due to several reasons: (a) large SiC substrate wafer up to 6 inch are commercially available, (b) SiC can be homoepitaxially grown avoiding lattice mismatch, (c) it can be either doped during crystal growth or ion implantation to achieve both n- and p-type conductivity and (d) both Si- and C-face can thermally grow oxide films [2]. The fact that SiC is the only compound semiconductor which shares its native oxide SiO$_2$ [3] with Si makes SiC a unique semiconductor material and makes it possible to fabricate standard MOS device structures, benefitting from the experience of silicon industry.

Although there has been much progress in SiC in recent years, and successful operation of many SiC prototype devices, but only very few commercial SiC metal oxide semiconductor field effect transistor (MOSFET) have entered the market [4]. This is due to several problems of the SiC MOS devices including high interface state density ($D_{it}$) at the SiC-SiO$_2$ interface, low channel mobility, unstable threshold voltages, high fixed charge densities in the oxide, and high oxide leakage currents. In the following chapters,
some of the properties of SiC will be described, leading to the difference in electrical properties of the semiconductor-insulator interface between Si and SiC.

1.2. Polytypism

Silicon carbide exhibits a two-dimensional polymorphism called polytypism, being one of the most exciting features of silicon carbide [5]. Different polytypes have significantly different properties, thus they can be considered to be different materials.

Fig. 1.1. The characteristic tetrahedron building block of SiC crystal. Four carbon atoms are covalently bonded with a silicon atom in the center. After ref. [5]
Fig. 1.2. Si-C-bilayer. After ref. [2]

Fig. 1.1 shows a tetrahedron of four carbon atoms with a silicon atom in the center, this is the basic building block of a SiC crystal [5]. Fig. 1.2 shows the layer structure of SiC, the tetrahedrally bonded silicon atoms linked to three C atoms within the bilayer and having a single bond linked to a carbon atom in layer above. The hexagonal frame of Si-C-bilayer is the basic component for the formation of polytypes [2]. Fig. 1.3 shows the same structure looking at it from above. In Fig. 1.3, the hexagonal frame is considered to be a close-packed layer of spheres which all have the same radius. The first layer which is at the very bottom is labeled as “A.” The relative position of the next layer on the top of the first layer cannot be directly above the first one, it will be either in the position “B” or position “C” for energy optimization. Every subsequent next layer will have to follow the same rule.
The Ramsdell notation is the most common naming convention used for SiC [6]. In the Ramsdell notation, the polytype’s name consists of a number followed by a letter. The number represents the period of the stacking sequences and the letter represents the crystal structure which the polytype forms. For a different sequence, the structure may be cubic, hexagonal, or rhombohedral, which is denoted by C, H and R. Polytype 2H has the stacking sequence ABAB… The three important polytypes 3C-SiC, 4HSiC and 6HSiC have stacking sequences ABCABC…, ABCBABC… and ABCACBABCACB… As mentioned above, SiC crystals never have any layer repeat due to energetic stability. Even with this restriction, infinitely many sequences are possible and in fact, over 200 have been
observed [7]. Table 1.1 listed some important material properties of 3C-SiC, 4HSiC and 6HSiC.

<table>
<thead>
<tr>
<th>Material parameters</th>
<th>3C-SiC</th>
<th>4H-SiC</th>
<th>6H-SiC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hexagonality</td>
<td>0</td>
<td>0.33</td>
<td>0.5</td>
</tr>
<tr>
<td>Lattice Constant (Å)</td>
<td>4.34</td>
<td>a=3.073</td>
<td>a=3.08</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c=10.053</td>
<td>c=15.117</td>
</tr>
<tr>
<td>Bandgap (eV)</td>
<td>2.36</td>
<td>3.2</td>
<td>3.0</td>
</tr>
<tr>
<td>Electron Saturation Velocity (10^7 cm/s)</td>
<td>2.7</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Electron Mobility (cm²/V-s)</td>
<td>800</td>
<td>900</td>
<td>400</td>
</tr>
<tr>
<td>Hole Mobility (cm²/V-s)</td>
<td>320</td>
<td>120</td>
<td>90</td>
</tr>
<tr>
<td>Thermal Conductivity (W/cm·°C)</td>
<td>3.6</td>
<td>3.7</td>
<td>4.9</td>
</tr>
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</table>

Table 1.1. Important material properties of 3C-SiC, 4HSiC and 6HSiC polytype. After ref. [2, 8, 9].

Each different polytype of silicon carbide has different electrical properties such as bandgap, electron saturation velocity and carrier mobility, due to its different crystal structure. Compared to 3C-SiC and 6H-SiC, the most common polytype of silicon carbide 4H-SiC has the highest mobility and the largest bandgap, this making 4H-SiC the best candidate for many applications. However, due to difficulties growing device quality 4H-SiC, in early days, 6H has been the more commonly used SiC polytype [10]. However, recently, 4H has become the dominant type.
1.3. Physical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Silicon</th>
<th>GaAs</th>
<th>4H-SiC</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band Gap (eV)</td>
<td>1.12</td>
<td>1.42</td>
<td>3.2</td>
<td>3.44</td>
</tr>
<tr>
<td>$n_i$ at 300K (cm$^{-3}$)</td>
<td>$10^{10}$</td>
<td>$1.8 \times 10^8$</td>
<td>$\approx 10^8$</td>
<td>$\approx 10^9$</td>
</tr>
<tr>
<td>Electron Saturation Velocity (10$^7$cm/s)</td>
<td>1.0</td>
<td>1.2</td>
<td>2.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Electric Breakdown Field (kV/cm)</td>
<td>300</td>
<td>400</td>
<td>2200</td>
<td>5000</td>
</tr>
<tr>
<td>Thermal Conductivity (W/cm$^{-2}$C)</td>
<td>1.3</td>
<td>0.55</td>
<td>3.7</td>
<td>1.3</td>
</tr>
<tr>
<td>Electron Mobility (cm$^2$/V-s)</td>
<td>1200</td>
<td>6500</td>
<td>800</td>
<td>1000</td>
</tr>
<tr>
<td>Hole Mobility (cm$^2$/V-s)</td>
<td>420</td>
<td>320</td>
<td>115</td>
<td>200</td>
</tr>
<tr>
<td>Lattice mismatch to GaN (%)</td>
<td>-17</td>
<td>-22</td>
<td>3.8</td>
<td>0</td>
</tr>
<tr>
<td>2014 Commercial Wafer Diameter (mm)</td>
<td>450</td>
<td>150</td>
<td>150</td>
<td>100</td>
</tr>
</tbody>
</table>

Table1.2 Properties of common polytypes of SiC compared with Si, GaAs, and GaN; data from refs. [2, 8, 9, 11, 12] and references therein.

Compared to Si and gallium arsenide (GaAs), which have been considered the two most mature materials in the semiconductor industry, SiC possesses some exciting physical properties. The impressive physical properties of SiC include excellent high temperature tolerance, high saturation velocity, high breakdown electric field, excellent resistance to radiation and chemical attack, high thermal conductivity, a high hardness value and transparency in the optical wavelengths range [2, 9]. In the family of wide bandgap semiconductors, gallium nitride (GaN) is the most significant competing wide band gap material. Although GaN has some advantage in terms of some of the physical properties
compared to SiC, GaN is still not mature enough for the commercial market due to some technological issues. Table 1.1 listed some important physical properties of 4H-SiC in comparison with Si, GaAs and GaN.

1.4. Silicon carbide applications

The physical properties mentioned above make SiC an ideal choice for electrical device applications in many different areas, such as high temperature, high power and high frequency electronic devices. For standard commercial silicon devices, 125°C is usually specified as the upper limit for proper operation. Temperatures above 125°C are considered to be a high temperature environment for an electronic device [13, 14]. The increasing intrinsic carrier density with increasing temperature is the issue that limits the high-temperature functionality of the p-n junction in silicon devices. The intrinsic carrier density $n_i$ of a semiconductor depends on temperature $T$, bandgap $E_g$ and effective density of states $N_c, N_v$ of the semiconductor as given by

$$n_i = (N_c \cdot N_v)^{1/2} \exp\left(-\frac{E_g}{2kT}\right)$$  \hspace{1cm} (1.1)

where $k$ is the Boltzmann’s constant.
Fig. 1.4. Comparison of intrinsic carrier concentration versus temperature for Si, 4H-SiC, 6H-SiC, and GaN.

The intrinsic carrier concentration for Si, 4H-SiC, 6H-SiC and GaN as a function of temperature is shown in Fig. 1.4. For Si, when the temperature increases from room temperature to 300°C, $n_i$ increases from the level of $10^{10}$ cm$^{-3}$ to the level of $10^{16}$ cm$^{-3}$ close to the dopant density level and most of the devices will not function properly. However, for 4H-SiC, at 300°C $n_i$ is only at the level of $10^5$ cm$^{-3}$ and thus the device can still function properly. Also, as shown in table 1.2, the thermal conductivity of SiC is
almost three times the thermal conductivity of Si. This means that SiC can remove heat much faster than Si. For the reasons mentioned above, SiC is ideal for high-temperature applications.

Being a wide bandgap semiconductor, SiC devices can be used in high-frequency applications due to their high saturation velocity and excellent thermal properties. SiC devices make an excellent high frequency oscillator. In fact, there are companies offering SiC MESFET devices for use in cellular base stations [5].

High-power applications are by far the biggest application area for SiC technology. For a power semiconductor device, the blocking voltage depends on the doping concentration. Decreasing the doping concentration will increase the blocking capability but result in an increased series resistance, leading to increased power loss. Compared to Si, SiC has a much higher breakdown electric field, thus at the same doping concentration, the SiC device blocking voltage is approximately 56.2 times higher than the blocking voltage of a Si device [15, 16]. SiC also has the highest thermal conductivity compare to any metal at room temperature [17], having the effect that it is much easier to cool down the device, eliminating the need for large size cooling system. Although SiC devices will be more expensive to manufacture compared to Si devices, the significant savings on the passive components and the cooling system will make the devices very attractive to a large customer base [5].
2.1. Introduction

As mentioned in the last chapter, some of silicon carbide’s physical properties make it an ideal material for several applications such as high-temperatures, high-frequency, and high power devices. In order to address the issues of current SiC MOS devices, it is necessary to develop a better understanding of the SiC/SiO$_2$ interface. Here, the silicon carbide metal-oxide-semiconductor capacitor is a powerful tool to study the SiC/SiO$_2$ properties. One of the properties that we can study using a SiC MOS capacitor is the generation lifetime, which we are going to discuss in this chapter. There are several technique for measuring the generation lifetime in semiconductors, one of the most powerful technique is the pulsed MOS capacitor lifetime measuring technique. This technique only needs a common MOS capacitor structure and is capable of measuring very short lifetimes. The original idea and its extensions can be found in [18-24] and a review of different method related to this technique can be found in Kang and Schroder [25]. Some work on characterizing the generation lifetime by using pulsed MOS capacitor measurement in SiC has been performed recently [26]. The pulsed MOS capacitor measurement can also be used to measure recombination lifetime. In this chapter, we are focusing on the pulsed MOS capacitor generation lifetime measurement in silicon carbide.
2.2. The Pulsed SiC MOS Capacitor

Fig. 2.1. Plot of (a) gate voltage versus time, (b) capacitance versus gate voltage and (c) capacitance versus time. After ref.[10, 27, 28].

For the pulsed MOS capacitor generation lifetime measurement, we measure the relaxation time of the MOS capacitor when it is pulsed to deep depletion. Fig. 2.1 illustrates the procedure of the pulsed MOS capacitor technique for a p-type substrate MOS capacitor. Before applying the voltage step, we assume the device is in accumulation and it is in equilibrium. A voltage step is applied at time 0 shown in Fig. 2.1(a), this will drive the
device from A to B in Fig. 2.1(b) and the device will be in deep depletion. In deep depletion, 

\( np < n_i^2 \) applies and the device is in a non-equilibrium state. Once the device is in deep depletion, thermally generated electron-hole pairs start to return the device back to equilibrium and form a full inversion layer, shown by the path B to C in Fig. 2.1(b). The recovery time \( t_r \) in Fig. 2.1(c) is determined by the thermal electron-hole pair generation mechanism.

There are several thermal generation components which are contributing to the recovery of the pulsed MOS capacitor, with every thermal generation component having a different generation rate. As shown in Fig. 2.2, the thermal generation components and its associated generation rates are (1) bulk generation in the space charge region characterized by the generation lifetime \( \tau_g \), (2) lateral surface space charge region generation adjacent to the gate characterized by the surface generation velocity \( s_g \), (3) surface space charge region generation under the gate characterized by the surface generation velocity \( s'_g \), (4) bulk generation in the quasi-neutral region characterized by the minority carrier diffusion length \( L_n \) and (5) surface generation at the back of the substrate characterized by the surface generation velocity \( s_c \) [28]. In our analysis, we assume that the substrate is thick enough that generation at the back contact is negligible. It is also assumed that surface generation adjacent to the gate and bulk generation in the space charge region depends linearly on the space-charge region width \( W - W_{inv} \) and surface generation below the gate and bulk generation in the quasi-neutral region are assumed to be independent of this width.
Fig. 2.2. Generation components described in the text which contribute to the recovery of the pulsed MOS-C depicted (a) on a band diagram and (b) in the device. After ref.[10, 27, 28].

For a pulsed MOS capacitor, the gate voltage is constant during the relaxation time, the capacitance change to the change in charge is [27]

\[
\frac{dQ_n}{dt} = \frac{qK_S\epsilon_0 C_{ox} N_A}{C^3} \frac{dC}{dt}
\]  \hspace{1cm} (2.1)

where \(dQ_n/dt\) is the thermal generation rate in Fig. 2.2
\[
\frac{dQ_n}{dt} = -\frac{q n_i W}{\tau_g} - \frac{q n_i s_g A_S}{A_G} - q n_i s'_g - \frac{q n_i^2 D_n}{N_AL'_n} \tag{2.2}
\]

where the area of the lateral space charge region \(A_S = 2\pi r W\), the gate area \(A_G = 2\pi r\) and \(L'_n\) is the effective diffusion length. If we only consider the space charge region generation rates

\[
\frac{dQ_{n,scr}}{dt} = -\frac{q n_i (W - W_{inv})}{\tau_{g,eff}} \tag{2.3}
\]

where \(W_{inv} = (4K_s\varepsilon_0\varphi_F/qN_A)^{1/2}\) and \(\tau_{g,eff}\) is the effective generation rate in the space charge region. Also, the effective surface generation velocity is

\[
s_{eff} = s'_g + \frac{n_i D_n}{N_A L'_n} \tag{2.4}
\]

Eq. 2.2 can be rewritten as

\[
\frac{dQ_n}{dt} = -q n_i \frac{W - W_{inv}}{\tau_{g,eff}} - q n_i s_{g,eff} \tag{2.5}
\]

The space charge region width \(W\) as a function of capacitance \(C\) is

\[
W = K_s\varepsilon_0 \frac{C_{ox} - C}{C_{ox} C} \tag{2.6}
\]
By combining Eqns. (2.2), (2.5) and (2.6), we can get

$$- \frac{d}{dt} \left( \frac{C_{ox}}{C} \right)^2 = \frac{2n_i C_{ox}}{\tau_{g,eff} N_A C_{inv}} \left( \frac{C_{inv}}{C} - 1 \right) + \frac{2K_{ox} n_i s_{g,eff}}{K_5 t_{ox} N_A} \quad (2.7)$$

Based on Eq. (2.7), we can plot $-d/dt \left( C_{ox}/C \right)^2$ versus $(C_{inv}/C - 1)$. This is the well-known Zerbst plot. From the slope of the Zerbst plot $2n_i C_{ox}/\tau_{g,eff} N_A C_{inv}$ we can extract the effective generation rate $\tau_{g,eff}$ and from the extrapolated intercept $2K_{ox} n_i s_{g,eff}/K_5 t_{ox} N_A$ we can extract the effective surface generation velocity $s_{eff}$. In our analysis, we neglect several details of this technique, more complete versions are available in refs. [25] and [27]. An experimental room-temperature C-t curve is shown in Fig. 2.3(a) and the corresponding Zerbst plot, is shown in Fig. 2.3(b) [27].

![Fig. 2.3. (a) Typical C-t transients during inversion layer formation and (b) the resulting Zerbst plot [27].](image)
2.3. Experimental Details, Results and Discussion

For the research presented in this chapter, we used 4H-SiC n-type and p-type samples grown by Cree Inc.. Both n-type and p-type samples are squares with approximately 5 mm sides, the n-type samples have a 10 µm epilayer doped to about $10^{16} \text{ cm}^{-3}$ and the p-type samples have a 5.2 µm epilayer doped to about $6.2 \times 10^{15} \text{ cm}^{-3}$. The samples were oxidized by Tami Isaacs-Smith and Prof. John Williams of the Auburn University Physics Department. The oxide thicknesses are 50 nm and 100 nm for different samples. For each sample, there are three sizes of circular contacts of diameters 145, 298 and 599 µm.

We should note that lifetime measurements with the pulsed MOS-C technique on a Si/SiO$_2$ device are generally made at room temperature. However, compared to Si, SiC has a much lower intrinsic carrier concentration. The intrinsic carrier concentration of SiC at 25 °C is only about $10^{-8} \text{ cm}^{-3}$, about 18 orders of magnitude lower than Si [8]. Thus, for making lifetime measurements with the pulsed MOS-C technique on a SiC/SiO$_2$ device, we have to raise the temperature in order to obtain reasonable recovery times.

In order to reduce series resistance, all the samples were cleaned with Acetone and IPA. After cleaning, the samples were attached to aluminum plates with silver paste. The aluminum plates were polished with sand paper on both sides and cleaned before attaching the samples. All the measurements were performed in an electrically isolated probe station with a maximum temperature of 400 °C. The capacitance was measured with an Agilent 4284 LCR meter and current measurements were made using an Agilent 4155C semiconductor parameter analyzer. Before making the C-t measurements, C-V measurements were done at room temperature for all the devices to analyze them.
For the C-t measurement, the SiC samples are first heated to and stabilized at 300°C, N₂ gas was flowing over the sample during the whole time. The C-t measurements are done in deep depletion of the capacitor. At 300°C, the recovery time of SiC capacitors is longer than 30min, in order to measure the recovery time, we heated the samples to 400°C for the C-t measurement. The devices we chose to measure are the ones with lower flat-band voltage shift ΔV₉ determined from the C-V measurements.

Fig. 2.4 shows the C-t response for (a) n-type and (b) p-type SiC MOS-C at 400°C.

Fig. 2.4 shows the C-t response for (a) n-type and (b) p-type SiC MOS-C at 400°C, and the recovery time for the p-type devices is about 4 times shorter than for n-type devices. The shorter recovery time is due to the high surface generation; the surface generation dominated the recovery process. This high surface generation is due to high interface state density and other defects in the oxide or at the oxide/semiconductor interface. Surface
generation can cause a highly nonlinear Zerbst plot [22] and is difficult to indicate bulk lifetime with such high surface generation. Hence, there is interest in the interface states at the SiC/SiO$_2$ interface, how high is the interface state density and how to extract it. More details about interface states at the SiC/SiO$_2$ interface will be discussed in the next chapter.

![Fig. 2.5. Comparison of C-V curves for (a) n-type and (b) p-type SiC MOS-C before and after annealing. T=400°C.](image)

It was also be found that some devices behave differently at 400°C than at room temperature. Fig 2.5 shows the changes of the C-V curves for both n-type and be type samples after heating to 400°C and cooling to room temperature, the $\Delta V_{fb}$ of the p-type device decreased dramatically, but the n-type devices show little or no decrease on $\Delta V_{fb}$. For samples which were heated up to 400°C and cooled to room temperature several times, $\Delta V_{fb}$ decreases each time it is heated up and cooled. The $\Delta V_{fb}$ decrease is due to the high temperature that anneals the interface states and oxide charges of the device. Fig. 2.6 shows
the C-t response for p-type SiC MOS-C after annealing. The surface generation is much lower than before annealing, but the surface generation still dominates at the beginning of the measurement before significant inversion charge has been generated. Further treatment has to be done to the device in order to lower the defects and determine the bulk lifetime form the pulsed MOS capacitor lifetime measuring technique.

Fig. 2.6. C-t response for p-type SiC MOS-C after heated up to 400°C and cooled down to room temperature 3 times.
CHAPTER 3. INTERFACE PASSIVATION FOR SILICON DIOXIDE LAYERS ON SILICON CARBIDE

3.1. Introduction

As mentioned in the first chapter, silicon carbide has the unique advantage in MOS technology compared to other wide-bandgap materials that SiO$_2$ can be grown as a native oxide by using thermal oxidation techniques similar to those used to grow SiO$_2$ on Si. Because of that, a major goal of the SiC research and development community is the development of SiC MOSFETs. However, in early days, the inversion channel mobility of 4H-MOSFETs has been surprisingly low, less than 10 cm$^2$/V s, which is approximately two orders of magnitude lower than the bulk mobility. It has been suggested the low inversion channel mobility of 4H-MOSFETs is due to the large number of interfacial defects at the SiO$_2$/SiC interface [29]. A lot of research efforts are focused on how to passivate the SiO$_2$/4H-SiC interface, and a variety of passivation methods has been proposed. In this chapter, we discuss recent passivation techniques for SiO$_2$/SiC interface passivation.

3.2. Nitrogen Passivation Annealing

For passivating the SiO$_2$/4H-SiC interface, efforts have been focused on oxidation procedures and post-oxidation anneals in various ambients such as NO, N$_2$O, NH$_3$ and H$_2$ [30]. Because of its ability to passivate Si dangling bonds at the SiO$_2$/Si interface, hydrogen has received much attention early on. However, introducing nitrogen at the SiO$_2$/4H-SiC interface by using post-oxidation anneals in NO and N$_2$O has rendered the best passivation
results [30]. It has been reported that effective channel mobilities are approaching 80 cm$^2$/V s for SiC MOSFETs by nitridation using NO and N$_2$O [31]. The interface trap density ($D_{it}$) near the conduction band edge reduces from larger than $10^{13} cm^{-2}eV^{-1}$ to around $10^{12} cm^{-2}eV^{-1}$ following nitridation [30].

NO passivation anneal is usually carried out at 1175°C for 2 hours at a flow rate of 0.5 liters/min [30]. Fig. 3.1 shows the interface trap density under different passivation conditions, the interface trap density is extracted by high-low frequency capacitance method using MOS capacitors. Details of the high-low frequency capacitance method will be explained in the next chapter.

![Fig. 3.1. Interface trap density in the upper 4H-CiC bandgap for unpassivated samples and sample passivated with NO and NO+H$_2$. [30]](image-url)
As shown in Fig. 3.1, $D_{it}$ measured on the passivated samples has been reduced by about an order of magnitude compared to the unpassivated samples. The $D_{it}$ can be further reduced by annealing the NO-passivated oxide in hydrogen atmosphere. Also, shown in Fig. 3.2, the effective channel mobility of passivated n-channel MOSFET samples was usually an order of magnitude higher compared to the unpassivated samples. Samples fabricated using the NO+H$_2$ annealing process show 25% to 30% higher Field-effect mobilities than samples using only the NO annealing process [30].

![Field-effect mobility before and after passivation for lateral MOSFETs.](image)

Fig. 3.2. Field-effect mobility before and after passivation for lateral MOSFETs. [30]

During the high-temperature NO passivation annealing process, additional oxide growth will occur and new defects will be generated by this unwanted oxidation. The trap density may not be lowered further due to the competition between defect passivation by
NO and defect generation by unwanted oxidation. This might be a limitation for the NO passivation annealing process. By using a proprietary process that introduces nitrogen without unwanted oxidation, lower trap density and higher channel mobility has been reported by Cree Inc. [30].

3.3. Phosphorus-Doped Gate Oxide

![Interface trap density in the upper 4H-CiC bandgap for unpassivated samples, NO passivated samples and PSG passivated samples under different passivation temperature](image)

Fig. 3.3. Interface trap density in the upper 4H-CiC bandgap for unpassivated samples, NO passivated samples and PSG passivated samples under different passivation temperature [32].

Recently, Okamoto proposed a new technique for fabricating 4H-SiC MOSFETs with high inversion channel mobility [32]. In this technique, P atoms were incorporated into the
SiO₂ side of the interface by using phosphoryl chloride (POCl₃) during post-oxidation annealing.

For this technique, an oxide layer on 4H-SiC is formed by dry oxidation at 1200°C. Then, the samples were annealed in a gas mixture of POCl₃, O₂ and N₂ for 10 minute at 900°C, 950°C and 1000°C. Following this, the samples were annealed for 30 minute in N₂ at the same temperature. The oxide thickness is nearly unchanged during the annealing process. The P-doped oxide layer at the interface has a dielectric constant around 3.8 to 4.1, which is close to the dielectric constant for SiO₂ (3.9). After the contact metal deposition, the samples were annealed again for 30 minute in N₂ at 400°C [32].

Fig. 3.3 shows the interface trap density under different PSG passivation temperature conditions, compared to samples with NO passivation and without any passivation. The interface trap density has been extracted by the high-low frequency capacitance method using MOS capacitors. As shown in Fig. 3.3, the Dᵢₜ value does not change for a PSG passivation anneal at 900°C, but the Dᵢₜ value will decrease if the annealing temperature is 950°C or higher. The Dᵢₜ value is smaller compared to NO passivated samples when the samples were annealed at 1000°C.

Fig. 3.4 shows the field-effect mobility of 4H-SiC MOSFETs fabricated with PSG passivation annealed at 1000°C compare with 4H-SiC MOSFETs fabricated with NO passivation annealing and unpassivated 4H-SiC MOSFETs. As shown in Fig. 3.4, the peak field-effect mobility is significantly higher than for samples with NO passivation annealing or those without any annealing.
3.4. Nitrogen Plasma Annealing

As mentioned earlier in this chapter, introducing nitrogen at the interface by using NO passivation annealing results in lower $D_{it}$ and a higher effective channel mobility improving the devices sufficiently for commercialization. However, there are limitations to NO passivation annealing due to the unwanted oxidation during the annealing process. Therefore, a process which could introduce more nitrogen at the interface and minimized the unwanted oxidation is needed to decrease the $D_{it}$ and increase effective channel mobility.

Recent reports show that using nitrogen plasma anneal to create a nitrogen containing layer at the SiO$_2$/SiC interface will reduce the $D_{it}$ of MOS capacitor [33]. The
nitrogen plasma annealing process was expected to improve the device performance for the following reasons: First, the unwanted oxidation can be reduced to minimum due to lack of oxygen in the nitrogen plasma. Second, carbon being interstitially injected into the SiC during oxidation, suspected to inhibit MOSFET carrier mobility, is correspondingly reduced [34]. Third, and most important, it can obtain higher N interface coverage. However, it has been reported that increasing the N interface coverage will potentially create “fast traps” [35].

The nitrogen plasma process flow is the following: A thin thermal oxide (~15nm) was first grown in O₂ ambient at 1150°C in atmospheric pressure, follow by Ar post-oxidation annealing for 30 minutes. Then, the samples were annealed by nitrogen plasma passivation for various hours in a different furnace. The nitrogen plasma passivation was performed under the condition of 1160°C, 3.0/min N₂ flow, 2.3 torr of pressure and 2kW of microwave power. This was followed by a 2 hour plasma recovery anneal at 1160°C in nitrogen ambient under atmospheric pressure. After the plasma treatment, another layer of SiO₂ was deposited by LPCVD at 700°C, 0.5 torr, following by a 2 hour densification anneal at 850°C in nitrogen.
CHAPTER 4. INTERFACE STATES AT THE SIC/SIO$_2$ INTERFACE

4.1. Interface States

It is often said that the real magic of silicon technology lies not in the silicon crystalline material but in silicon dioxide and its interface with silicon [36]. Silicon dioxide is often treated as an ideal insulator, where there are no unwanted charges and states at the interface of silicon and silicon dioxide. But in reality, the silicon/silicon dioxide interface and the bulk silicon dioxide in a device are far from electrically neutral. This may be caused by (1) interface trap charges at the silicon/silicon dioxide interface, (2) fixed charges, (3) oxide trapped charges and (4) mobile ionic charges trapped within the oxide itself, which are often created during the fabrication process. These four general types of charges are shown in Fig. 4.1. For a device which has a semiconductor/oxide interface, the electronic properties are very sensitive to the quantity of the interface state and how it distributed in the semiconductor bandgap.[36]

Fig. 4.1. Charges and their locations in an oxide/semiconductor cross sections.
Fig. 4.2. Energy-band diagram of a MOS structure, depicting the distribution of interface states in the bandgap of the semiconductor at the oxide/semiconductor interface.

As shown in Fig. 4.1 and Fig. 4.2, interface states are located at or very close to the oxide/semiconductor interface and have an energy distribution within the bandgap and even extend into the conduction and valence band of the semiconductor. The interface states are attributed to dangling bonds, vacancies, atom-like bonds and anti-site defects at the oxide/semiconductor interface. When electrons or holes are trapped in these interface states, they will act like positive or negative charges at the interface. Just like the impurity energy states in the bulk of a semiconductor, the probability for an interface state to be
occupied by an electron or hole depends on the energetic location of the interface state relative to the Fermi level at the interface. As shown in Fig. 4.2, the energetic location of the interface states are fixed relative to the semiconductor band edges at the interface, so when the surface potential changes, which means the Fermi level at the interface changes, the interface states occupation probability by electron or holes will also changes.

Presumably, there are two types of interface states, donor states and acceptor states. A donor state is neutral when occupied by an electron and becomes positively charged when empty. On the other hand, an acceptor state is neutral when empty and becomes negatively charged when accepting an electron. The distribution function (occupancy) for donor states is

\[
F_{SD}(E_d) = \frac{1}{1 + 2\exp\left[\frac{E_F - E_d}{kT}\right]} \quad (4.1)
\]

and the distribution function (occupancy) for acceptor states is

\[
F_{SA}(E_a) = \frac{1}{1 + 4\exp\left[\frac{E_a - E_F}{kT}\right]} \quad (4.2)
\]

where \(E_d\) is the energy of the donor state, and \(E_a\) is the energy of the acceptor state.
Fig. 4.3. General interface states system consisting of both donor and acceptor states. This is often expressed by an equivalent distribution with a charge-neutrality level $E_{CNL}$ above which the states are acceptor type and below which they are donor type. When $E_F$ is above (below) $E_{CNL}$, net charge is $-$(+).

For a given interface, it is usually considered that it has both donor states and acceptor states. The interface state density ($D_{it}$) is the most common unit to quantify interface states, and it is convenient to express the interface states using an equivalent interface state density ($D_{it}$) energy distribution, associated with the energy band diagram. In Fig. 4.3, there is an energy level called the charge-neutrality level $E_{CNL}$. Interface states which energy levels are above the $E_{CNL}$ are to be considered as acceptor states, since when the Fermi level $E_F$
at the interface is above $E_{CNL}$, the states below $E_F$ are occupied by electrons and negatively charged. Interface states which energy levels are below the $E_{CNL}$ are to be considered as acceptor states, since when the Fermi level $E_F$ is below $E_{CNL}$, the states above $E_F$ are empty and positively charged. When $E_F$ is right at $E_{CNL}$ at the interface, all the states are neutral.

By assuming that the occupancy of an electron for a trap takes a value of 0 when above $E_F$ and 1 when below $E_F$ at room temperature, we can calculate the concentration of trapped charge at the interface $Q_{it}$ by:

$$P = -Q_{it}.$$ \[\text{Eq. 4.3}\]

$$P(R_{TUV}) = Q_{it}.$$ \[\text{Eq. 4.4}\]

The unit of $Q_{it}$ is C/cm$^2$. Also, the interface state density $D_{it}$ are distributed across the energy bandgap at the interface and its distribution can be expressed as:

$$D_{it} = \frac{1}{q} \frac{dQ_{it}}{dE} \text{ # of traps/cm}^2\text{-eV} \quad (4.4)$$

In Eq. 4.4, the change in $Q_{it}$ is determined by the movement of $E_F$ at the surface, in other words, changes in surface potential $\phi_s$ can be used to determine $D_{it}$. More details will be discussed in the next section [37]. When applying a voltage to the gate of an MOS structure, $\phi_s$ will be changed by the bias, thereby the charges at the interface will also be changed. As mentioned above, the oxide/semiconductor interface states will be positively charged, negatively charged or neutral, depending on the location of the Fermi level at the
interface. The charge balance between $Q_{it}$ and the space charge $Q_{SC}$ in the space-charge region will determine the band bending within the semiconductor.

![Equivalent circuits including interface state effects](image)

Fig. 4.4. (a) (b) Equivalent circuits including interface state effects, $C_{it}$ and $R_{it}$ [38]. (c) Low-frequency limit. (d) High-frequency limit. After ref. [27]

For Silicon, the interface state density can have a value as high as $10^{14}$ cm$^{-2}$ due the atom area density at the interface. The distribution of the interface states typically has an energy range from 0.1 eV to the entire bandgap, this makes the interface state density per unit energy as high as $10^{15}$ cm$^{-2}$ eV$^{-1}$. When the interface has such high $D_{it}$, the Fermi level $E_F$ will be pinned at a certain energy level. This effect is known as Fermi level pinning. Fermi level pinning depends on the energy distribution of the interface states. $E_F$ is usually pinned very close to the charge-neutrality level $E_{CNL}$. The further $E_F$ deviates from $E_{CNL}$, more interface states will be charged. As a consequence, the space charges within the semiconductor will not be able to compensate the high value of interface state charges at the interface. Even with changing the external electric field by changing the gate voltage,
E_F can only shift for a small amount within the band of interface states with respect to the charge-neutrality level [39].

As the energy location of the Fermi level E_F changes at the oxide/semiconductor interface, the interface trap charge density, Q_{it} will also change. Such increase or decrease of charges at the interface will affect the MOS capacitance and modify the ideal MOS curve. Fig. 4.4 shows the basic equivalent circuit that incorporates the effect of the interface states [38]. In Fig 4.4 (a), C_{ox} represents the oxide capacitance and C_D represents the space-charge region capacitance in the semiconductor in a MOS device. The capacitance and resistance associated with interface states are represented by C_{it} and R_{it}. C_{it} and R_{it} are also energy dependent. C_{it}R_{it} product will define the interface trap life time \tau_{it} that can be defined by the product of C_{it} and R_{it}. By using the trap life-time \tau_{it}, the frequency behavior of the interface states can be determined. Fig. 4.4 (a) can be converted into an equivalent circuit as shown in Fig. 4.4 (b), C_p and G_p represent the frequency-dependent capacitance and the frequency-dependent conductance. C_p and G_p can be calculated from

\[
C_p = C_D + \frac{C_{it}}{1 + \omega^2 \tau_{it}^2}
\tag{4.5}
\]

and

\[
\frac{G_p}{\omega} = \frac{C_{it}\omega \tau_{it}}{1 + \omega^2 \tau_{it}^2}
\tag{4.6}
\]

Also, the equivalent circuits for the low-frequency and high-frequency limits are shown in Fig. 4.4 (c) and Fig. 4.4 (d). As shown in Fig. 4.4 (c), for the low-frequency limit, R_{it} is
set to zero, and $C_D$ is parallel to $C_{it}$. As shown in Fig. 4.4 (d), for the high-frequency limit, the $C_{it}$–$R_{it}$ branch is ignored or open. We assume that the low-frequency signal is low enough that all of the interface states will respond and the high-frequency signal is high enough that interface trap life time $\tau_{it}$ is not short enough to respond. The low-frequency $C_{LF}$ and the high-frequency $C_{HF}$ can be determined from [37]:

$$C_{LF} = \frac{C_{ox}(C_D + C_{it})}{C_{ox} + C_D + C_{it}} \quad (4.7)$$

$$C_{HF} = \frac{C_{ox}C_D}{C_{ox} + C_D} \quad (4.8)$$

For different semiconductors, the energy position of the charge-neutrality level, $E_{CNL}$ is different. The energy location of $E_{CNL}$, bandgap $E_g$ and electron affinity in various semiconductors are listed in Table 4.1. The energy value of the charge-neutrality level (CNL) is respected to the valance band energy level, $E_V$. More details on calculating CNL for compound semiconductor materials can be found in [40, 41].
### Table 4.1 Parameters for the various semiconductors – bandgap, electron affinity (EA) and charge-neutrality level (CNL). After ref. [40, 41].

<table>
<thead>
<tr>
<th>Material</th>
<th>Gap (eV)</th>
<th>EA (eV)</th>
<th>CNL (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.12</td>
<td>4.05</td>
<td>0.2</td>
</tr>
<tr>
<td>Ge</td>
<td>0.67</td>
<td>4.13</td>
<td>0.1</td>
</tr>
<tr>
<td>3C-SiC</td>
<td>2.35</td>
<td>4.55</td>
<td>1.3</td>
</tr>
<tr>
<td>6H-SiC</td>
<td>3.05</td>
<td>3.85</td>
<td>1.55</td>
</tr>
<tr>
<td>4H-SiC</td>
<td>3.25</td>
<td>3.65</td>
<td>1.55</td>
</tr>
<tr>
<td>AlP</td>
<td>2.56</td>
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<tr>
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<td>4.06</td>
<td>0.16</td>
</tr>
<tr>
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</tr>
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<td>0.6</td>
<td>3.3</td>
</tr>
<tr>
<td>ZnO</td>
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<td>4.6</td>
<td>3.27</td>
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4.2. Conductance Measurement

There are several techniques being employed to measure and characterize the interface states in a MOS structure. Two popular techniques we performed in our work will be discussed in this and the next section. The two techniques are the conductance measurement and the high-low frequency capacitance method. Other techniques have not been used because of their respective shortcomings and the limitations of our instruments and sample device.

Fig. 4.5. Equivalent circuits for conductance method; (a) standard MOS capacitor, (b) simplified circuit of (a), (c) measured circuit, (d) including series resistance $r_s$ and tunnel conductance $G_t$ and (e) admittance circuit. After ref. [27]
The conductance method was first proposed by Nicollian and Goetzberger in 1967, it is one of the most complete, sensitive and accurate methods to evaluate the interface trap density \( D_{it} \) [42, 43]. The conductance method can be used to measure \( D_{it} \) values on the order of \( 10^9 \text{cm}^{-2}\text{eV}^{-1} \) and sometimes even lower. By using the conductance method, we can not only extract the \( D_{it} \) value in both the depletion and weak inversion portion of the bandgap, the capture cross-section of the interface states and the fluctuation of the surface potential \( \phi_s \) can also be extracted as well. The conductance method is based on measuring the conductance \( G_m \) and capacitance \( C_m \) of a MOS capacitor as a function of bias voltage and frequency, and subsequently calculating the parallel conductance \( G_P \) by solving the small signal equivalent circuit. \( G_P \) represents the loss mechanism occurring when the interface states capture and emit carriers, and is used to extract the interface state density.

Fig. 4.5 shows the equivalent circuits of an MOS capacitor used for the conductance method [27]. In Fig. 4.5 (a), \( C_{ox} \) is the oxide capacitance, \( C_S \) is the semiconductor capacitance, \( C_{it} \) is the interface trap capacitance and \( R_{it} \) is the resistance representing the loss mechanism when the interface states capture and emit carriers. In order to obtain the parallel conductance \( G_P \), we can replace the circuit of Fig. 4.4(a) by the circuit of Fig. 4.4(b), in which \( C_P \) and \( G_P \) are given by

\[
C_P = C_S + \frac{C_{it}}{1 + (\omega \tau_{it})^2} \tag{4.9}
\]

\[
\frac{G_P}{\omega} = \frac{q\omega \tau_{it} D_{it}}{1 + (\omega \tau_{it})^2} \tag{4.10}
\]
where $C_{it}=q^2D_{it}$, $\tau_{it}=R_{it}C_{it}$ and $\omega= 2\pi f$ ($f$ is the measurement frequency), $\tau_{it}$ is the interface state time constant. Further details of $\tau_{it}$ will be discussed in the next chapter. For Eq. (4.9) and Eq. (4.10), it is assumed that the interface state is a single energy level trap in the energy gap. However, the interface states have a continuous distribution in energy within the semiconductor energy gap at the semiconductor/oxide interface. For interface states, the capture and the emission primarily happens within a few kT/q above or below the Fermi level $E_F$, therefore, a time constant dispersion and normalized conductance is given by [42]

$$\frac{G_P}{\omega} = \frac{qD_{it}}{2\omega\tau_{it}} \ln[1 + (\omega\tau_{it})^2]$$

(4.11)

In practical measurements, the impedance meters will assume that the device consists of a parallel $C_m$-$G_m$ combination as the equivalent circuit shown in Fig. 4.5(c) [27], where $C_m$ is the measured capacitance and $G_m$ is the measured conductance. By converting the circuit in Fig. 4.5(c) to the circuit in Fig. 4.5(b), we can express $G_p/\omega$ in terms of $C_m$, $C_{ox}$ and $G_m$ as

$$\frac{G_P}{\omega} = \frac{\omega G_m C_{ox}^2}{G_m^2 + \omega^2 (C_{ox} - C_m)^2}$$

(4.12)

Here, we assume the series resistance is negligible.

In order to extract the $D_{it}$ value, the conductance and capacitance are measured as a function of frequency and plotted as $G_P/\omega$ versus $\omega$ [27]. For Eq. (4.10), the maximum $G_p$
occurs at $\omega=2/\tau_{it}$ where $D_{it}=2.5G_P/q\omega$, and for Eq. (4.11), the maximum $G_P$ occurs at $\omega=1/\tau_{it}$ where $D_{it}=2G_P/q\omega$. In the $G_P/\omega$ versus $\omega$ plot, the $D_{it}$ and $\tau_{it}$ value can be determined by the peak $G_P$ and its peak frequency $\omega$. Fig. 4.6 shows a series of $G_P/\omega$ under different bias in the depletion region for a silicon MOS capacitor.

![Figure 4.6](image)

**Fig. 4.6.** $G_P/\omega$ versus $\omega$ in under different bias measured on a silicon MOS capacitor.

Fig. 4.7 shows a comparison of an experimental data measured from a Si/SiO$_2$ interface and the calculated $G_P/\omega$ by using Eq. (4.10) and Eq. (4.11). As shown, the experimental curve is much broader compare to two calculated curves. In a real MOS device there will always be surface potential fluctuations due to non-uniformities in interface traps, oxide
charge and doping density. The surface potential fluctuations will cause dispersion of the interface trap time constant and result in a broader curve [27]. The analysis of the experimental data will become more complicated by considering the surface potential fluctuations, and Eq. (4.11) becomes [43]

\[
\frac{G_P}{\omega} = \frac{q D_{it}}{\sqrt{2\pi\sigma_{US}^2}} \int_{-\infty}^{\infty} \ln\left[1 + \left(\omega \tau_{it} e^{-\Delta U_s}\right)^2 \right] \frac{e^{-\Delta U_s^2}}{2\omega \tau_{it} e^{-\Delta U_s}} d\Delta U_s \tag{4.13}
\]

where \(\Delta U_s\) is the difference of the normalized surface potential \(U_s\) and the normalized mean surface potential \(\bar{U}_s\), and \(\sigma_{US}\) standard deviation of the surface potential.

The surface potential fluctuations are now considered by fitting Eq. (4.13) to the experimental data. During the fitting process, we can not only extract the accurate \(D_{it}\) value but also determine the interface state time constant \(\tau_{it}\) and the standard deviation of the surface potential \(\sigma_{US}\). In addition, the interface state capture cross section can be obtained by using the extracted \(\tau_{it}\). Further details will be discussed in the next chapter.

In order to determine the energy level of the extracted interface state relative to the valence band, the surface potential \(\phi_s\) under the bias condition is calculated using [44]

\[
\phi_s = \frac{qK_s\epsilon_0 N_B A^2}{2C_d^2} \tag{4.14}
\]

and
\[ E - E_V = \frac{E_g}{2} - (kT) \ln \left( \frac{N_B}{n_i} \right) + \phi_s \]  \hspace{1cm} (4.15)

where \( K_s \) is the semiconductor dielectric constant, \( N_B \) is the semiconductor substrate doping concentration and \( A \) is the measured area.

Fig. 4.7. \( G_p/\omega \) versus \( \omega \) for experimental data measured from Si/SiO\(_2\) interface, single level [equation(4.10)] and continuum [equation(4.11)]. For all curves: \( D_{it}=1.9\times10^9 \text{cm}^{-2}\text{eV}^{-1}, \tau_{it}=7\times10^{-5} \text{s} \) [27].
Fig. 4.8. Interface trap density $D_{it}$ versus energy for quasi-static and conductance method on (a) (111) n-Si and (b) (100) n-Si. [27]

For the conductance measurement, a wide range of measurement frequencies is needed. Using such a wide measurement frequency range allows extraction of a broader energy range for the interface states. Fig. 4.8 shows the comparison of the extracted interface trap density $D_{it}$ measured by the conductance measurement and the quasi-static method on (111) and (100) n-type Silicon [27, 45, 46]. More details of the quasi-static method will be discussed in the next section. Although the two methods agree well with each other in the overlapping energy range, as shown Fig. 4.8, the $D_{it}$ data measured by the quasi-static method cover a much broader extracted energy range. Compared to the quasi-static method, the conductance measurement can only extract $D_{it}$ for a much narrower energy
range, only being able to measure $D_a$ in the depletion and weak inversion region of the MOS capacitor. In order to have a more accurate result in terms of energy resolution, the signal amplitude of the applied small AC signal should be kept around 50mV or lower to prevent the rise of unwanted conductance from the harmonics of the signal frequency.

When measuring a MOS capacitor which has a thin oxide, the oxide leakage current and the series resistance will no longer be negligible. In order to take the oxide leakage current and the series resistance into account, a more complete equivalent circuit model is needed. Fig 4.5 (d) shows the equivalent circuit includes the tunnel conductance $G_t$ and the series resistance $r_s$, hence Eq. (4.12) becomes [47, 48]

$$\frac{G_p}{\omega} = \frac{\omega(G_c - G_t)C_{ox}^2}{G_c^2 + \omega^2(C_{ox} - C_c)^2} \quad (4.16)$$

where

$$C_c = \frac{C_m}{(1 - r_s G_m)^2 + (\omega r_s C_m)^2} \quad (4.17)$$

and

$$G_c = \frac{\omega^2 r_s C_c C_m - G_m}{r_s G_m - 1} \quad (4.18)$$
The series resistance $r_s$ can be determined by biasing the MOS capacitor into the strong accumulation and using [43]

$$r_s = \frac{G_{ma}}{G_{ma}^2 + \omega^2 C_{ma}^2} \quad (4.19)$$

where $G_{ma}$ and $C_{ma}$ represents the measured conductance and capacitance in accumulation mode. The tunnel conductance can be determined as $\omega \to 0$ in Eq (4.18) [43].

In order to reduce the unwanted parasitic effects due to the contact, device design and the measurement setup, Prof. James A. Cooper of the Purdue University Electrical and Computer Engineering Department proposed a parasitic reduction method. By biasing the device into strong accumulation, we measure the real and imaginary parts of the admittance as a function of frequency. This represents $C_{ox}$ in series unwanted parasitic and shown as $Y_S$ in Fig. 4.5 (e). And then subtract this series admittance from the measured admittance at each frequency, this leave us with the depletion admittance $Y_p$ that represents $G_p$ and $C_p$ in Fig.4.5 (b). $G_p$ and $C_p$ now become

$$G_p = \frac{\left( \frac{G_m}{G_m^2 + \omega^2 C_m^2} \right) - \left( \frac{G_{ma}}{G_{ma}^2 + \omega^2 C_{ma}^2} \right)}{\left( \frac{G_m}{G_m^2 + \omega^2 C_m^2} \right) - \left( \frac{G_{ma}}{G_{ma}^2 + \omega^2 C_{ma}^2} \right)^2 + \omega^2 \left( \frac{C_m}{C_m^2 + \omega^2 C_m^2} \right) - \left( \frac{C_{ma}}{C_{ma}^2 + \omega^2 C_{ma}^2} \right)^2} \quad (4.20)$$

And
\[
C_p = \frac{\left(\frac{C_m}{G_m^2 + \omega^2 C_m^2}\right) - \left(\frac{C_{ma}}{G_{ma}^2 + \omega^2 C_{ma}^2}\right)}{\left[\left(\frac{G_m^2}{G_m^2 + \omega^2 C_m^2}\right) - \left(\frac{G_{ma}^2}{G_{ma}^2 + \omega^2 C_{ma}^2}\right)\right]^2 + \omega^2 \left[\left(\frac{C_m}{G_m^2 + \omega^2 C_m^2}\right) - \left(\frac{C_{ma}}{G_{ma}^2 + \omega^2 C_{ma}^2}\right)\right]^2}
\]

(4.21)

where \(G_{ma}\) and \(C_{ma}\) are the measured conductance and capacitance in accumulation mode.

4.3. **High-low Frequency Capacitance method**

There is another interface state measuring technique for extracting the interface state density by measuring the capacitance at a fixed high and a fixed low frequency, known as the high-low frequency capacitance method. Compared with the conductance measurement discussed in the last section, the high-low frequency capacitance method is easier and faster to perform. The idea behind the high-low frequency capacitance method is intuitively simple, measure the capacitance at a high enough frequency that no interface state can respond to the high frequency signal and measure the capacitance at a low enough frequency that all of the interface states will respond to the low frequency signal, the interface state density \(D_{it}\) can be extracted from the difference of the two capacitance-voltage curves.

For discussing the detail theory of the high-low frequency capacitance method, we first need to address some useful terms. The interface state associated capacitance \(C_{it}\) and interface state density \(D_{it}\) has a relationship of,

\[
C_{it} \equiv \frac{dQ_{it}}{d\phi_s}
\]

(4.21)
\[ \frac{d\phi_s}{dV} = \frac{C_{ox}}{C_{ox} + C_d + C_{lt}} \]  

(4.22)

where \( V = V_{ox} + \phi_s \). By substitution of Eq. (4.21) into Eq. (4.22), Eq. (4.22) now becomes

\[ D_{lt} = \frac{C_{ox}}{q^2} \left[ \left( \frac{d\phi_s}{dV} \right)^{-1} - 1 \right] - \frac{C_d}{q^2} \]  

(4.23)

Then we can calculate the \( D_{lt} \) value by obtain the \( \phi_s - V \) relationship from the capacitance measurement [37].

Three different capacitance methods have been commonly used for measuring \( D_{lt} \), they are called the high-frequency method, the low-frequency method and the high-low frequency method. The high-frequency method was purposed by Terman in 1962 [49]. For the high-frequency method, the high-frequency equivalent circuit shown in Fig. 4.4(d) does not contain the component of the interface state associated capacitance \( C_{it} \). By measuring the capacitance at high frequency, the depletion-layer capacitance \( C_d \) can be determine by the capacitance \( C_{HF} \) using [37]
Also, the surface potential $\phi_s$ can calculated by using Eq. (4.14), and by using the $\phi_s - V$ relationship, the $D_{it}$ value can be determined by using Eq. (4.23).

The low-frequency method sometimes called quasi-static method was purposed by Berglund in 1967 [50]. Different than the high-frequency method, the $\phi_s - V$ relationship is determine by the capacitance $C_{LF}$ measured at low frequency. Based on the low-frequency equivalent circuit in Fig. 4.4(c) and Eq. (4.22),

$$
\frac{d\phi_s}{dV} = \frac{c_{ox}}{c_{ox} + c_{D} + c_{it}}
$$

$$
= 1 - \frac{c_{D} + c_{it}}{c_{ox} + c_{D} + c_{it}}
$$

$$
= 1 - \frac{c_{LF}}{c_{ox}} \quad (4.25)
$$

By integrating equation (4.25) over two applied voltage we get

$$
\phi_s(V_2) - \phi_s(V_1) = \int_{V_1}^{V_2} \left(1 - \frac{c_{LF}}{c_{ox}}\right) dV + constant \quad (4.26)
$$

For Eq. (4.26), the surface potential can be determined at any applied voltage by integrating Eq. (4.25). The constant in Eq. (4.25) represents the starting point of the $\phi_s$ either in the accumulation or the strong inversion region, $\phi_s$ has a weak dependence on the supply
voltage in these two regions [37]. By knowing $\phi_s$, the depletion-layer capacitance $C_d$ can be determined using Eq. (4.14) with the semiconductor substrate doping concentration.

In 1971, Castagne and Vapaille purposed the high-low frequency method which combines the high-frequency and the low-frequency method [51]. The advantage of the high-low frequency method is that no theoretical calculation is needed for comparison, since especially for non-uniform doping profiles such theoretical calculation is highly complicated. With the low-frequency capacitance $C_{LF}$ in Fig. 4.4(c)

$$C_{LF} = \frac{c_{ox}(c_D + c_{it})}{c_{ox} + c_D + c_{it}}$$  \hspace{1cm} (4.27)

and Eq. (4.24), we can express

$$C_{it} = \left(\frac{1}{c_{LF}} - \frac{1}{c_{ox}}\right)^{-1} - C_D$$

$$= \left(\frac{1}{c_{LF}} - \frac{1}{c_{ox}}\right)^{-1} - \left(\frac{1}{c_{HF}} - \frac{1}{c_{ox}}\right)^{-1}$$  \hspace{1cm} (4.28)

By defining the difference in capacitance between high-frequency and low-frequency as $\Delta C \equiv C_{LF} - C_{HF}$, and Eq. (4.21), the interface state density $D_{it}$ can be directly obtained by [37]
\[
D_{it} = \frac{c_{ox}}{q^2} \left[ \left( \frac{1}{\Delta C/c_{ox} + c_{HF}/c_{ox}} - 1 \right)^{-1} - \left( \frac{1}{c_{HF}/c_{ox}} - 1 \right)^{-1} \right] \tag{4.29}
\]

\[
\quad = \frac{\Delta C}{q^2} \left( 1 - \frac{c_{HF} + \Delta C}{c_{ox}} \right)^{-1} \left( 1 - \frac{c_{HF}}{c_{ox}} \right)^{-1}
\]

at each bias. Fig. 4.9 shows the capacitance measured at high frequency and low frequency on a Silicon capacitor.

![Capacitance measured on silicon MOS capacitor at high and low frequency.](image)

Fig. 4.9. Capacitance measured on silicon MOS capacitor at high and low frequency.
The energy level of the extracted interface state must to be known in order to obtain the $D_{it}$ profile. Similar to the conductance method, the energy level of the extracted interface state can be calculated from the capacitance measured at high frequency using Eq. (4.14) and Eq. (4.15). Fig. 4.10 shows the $D_{it}$ profile extracted from the capacitance data in Fig. 4.9.

Fig. 4.10. $D_{it}$ profile measured using high-low frequency method on silicon MOS capacitor.
4.4. Conductance Measurement of SiC MOS-C

<table>
<thead>
<tr>
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<th>Substrate</th>
<th>Doping (cm⁻³)</th>
<th>( t_{ox} ) (nm)</th>
<th>Contact Metal</th>
<th>Anneal</th>
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</thead>
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</tr>
<tr>
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<td>( 5.5 \times 10^{15} )</td>
<td>60</td>
<td>Al</td>
<td>N plasma</td>
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</tbody>
</table>

Table 4.2. Basic sample information used for this research.

Table 4.2 shows the basic information of the samples used for the research presented in this chapter. We used 4H-SiC n-type and p-type samples grown by Cree Inc.. Samples N2(2), P5 NO0219, PSG225, 142, 143, 144 and 145 were oxidized by Prof. Sarit Dhar of the Auburn University Physics Department. All these samples underwent the NO passivation during the fabrication process. Sample Cree 1, Cree 2, Cree 3 and Cree 4 were...
oxidized by Cree Inc.. Sample N2(2) and P5 are used to make lifetime measurements and were heated to 400°C several times.

In order to minimize the effect of gate leakage current, we choose a device on the samples which had a low gate leakage current for the conductance measurement. Both n-type and p-type substrate samples were measured. The capacitance and conductance data were measured with an Agilent 4294A impedance meter, with a frequency range of 40Hz to 110MHz.

In order to accurately identify the conductance peak, the frequency of the peak point should be at least 5 times above (or below) the minimum (or maximum) measurement frequency. We measured the conductance and the capacitance with a frequency sweep range of 40Hz to 10MHz to minimize the noise at high frequencies.

![Fig. 4.11. Small signal ac interface state conductance $G_p/\omega$ as a function of $\omega$ on (a) P5L01 and (b) P5L04 at room temperature.](image)

52
Fig. 4.11 shows the data of interface state conductance $G_p/\omega$ as a function of $\omega$ on two different devices on P5 at room temperature. In order to determine the energy of the interface states relative to the valence band energy, the surface potential $\phi_s$ is calculated by using Eq. (4.14) and the energy is then calculated using Eq. (4.15).

Fig. 4.12. Interface trap capture cross-section vs energy for P5L05.

Fig. 4.12 shows the interface trap carrier capture cross-section extracted by using curve fitting on the conductance data for P5L05. As shown in Fig. 4.12, the interface trap capture cross-section increases exponentially as the energy of the interface traps increases. With
increasing interface trap energy close to mid-gap, the capture cross-section becomes unrealistically large.

As shown in Fig. 4.11, for P5L01, interface traps responded at higher frequencies and we extracted $D_i$ for a larger energy range compared to P5L04. P5L01 has a larger flatband voltage shift than P5L04, which can be attributed to mobile ions in the oxide closer to the SiC/SiO$_2$ interface. To determine the oxide mobile ion density, we conducted bias temperature stress (BTS) measurements on P5, N2(2) and Cree 1 samples. P5 and N2(2) show $Q_m \approx 10^{12} \text{cm}^{-2}$ and Cree1 shows only $Q_m \approx 10^{10} \text{cm}^{-2}$. However, after Cree 1 was heated to 400°C and cooled to room temperature, the mobile ion density dramatically increased to $Q_m \approx 10^{12} \text{cm}^{-2}$.

![Fig. 4.13](image)

(a) (b)

Fig. 4.13. Small signal ac interface state conductance $G_p/\omega$ as a function of $\omega$ on P5L04 (a) before and (b) after moving the ions close to the interface.
In order to understand how the mobile ions in the oxide affect the conductance measurement, we moved the mobile ions with BTS and repeated the conductance measurements the following day. During BTS, we first heated the sample to 200°C and applied either +5 V or -5 V for 5 minutes to move the ions close to or away from the SiC/SiO₂ interface. After 5 minutes of applying bias at 200°C, we turned the heater off to cool the sample, still applying the bias during cool down. The bias is removed when the sample temperature is lower than 40°C.

![Diagram](image)

Fig. 4.14. (a) Extracted Dit profile and (b) energy range at different conditions on P5 sample.

Fig. 4.13 shows the conductance for P5L04 before and after moving the ions in SiO₂ close to the SiC/SiO₂ interface by BTS. As shown in Fig.4.13, after moving the ions close to the SiC/SiO₂ interface, the interface traps responded at higher frequencies and allowed us to extract Dit over a larger energy range. The energy range increased from 0.26 eV to 1.28 eV. Fig. 4.14 shows the extracted Dit profile and the extracted range for P5 under
different conditions. As shown in Fig. 4.14, although the extracted energy range is different, the extracted $D_{it}$ matches within the measured range. We were not able to measure P5L04 after moving the ions away from the interface because P5L04 failed during BTS.

We also performed the same procedure on Cree 1. Fig. 4.15 shows results of conductance measurements for Cree 1-3L04 before and after moving the ions in the SiO$_2$ close to or away from the SiC/SiO$_2$ interface. Same as P5, Cree1 also shows increased extracted energy range when the mobile ions in the oxide are closer to the SiC/SiO$_2$ interface. Fig. 4.16 shows the extracted $D_{it}$ profile and the extracted range for Cree 1 under different conditions.

![Fig. 4.15. Small signal ac interface state conductance $G_p/\omega$ as a function of $\omega$ on Cree1-3L04 after moving the ions (a) away from and (b) close to the interface.](image.png)
In order to understand the oxide charge behavior at room temperature, we measured the C-V by sweeping in different directions on Cree 1, NO0219 and PSG0225. Fig. 4.17 summarizes the results with Cree 1 and PSG0225 showing ion drift behavior in the oxide, NO0219 showing electron injection and Cree 2 showing almost no oxide charge behavior.

We also measured BTS on NO0219 and PSG0225 after heating the sample to 200°C at +5V for 5 minutes, and turning the heater off with the bias applied during cool down. Fig. 4.18 shows the C-V curves for NO0219 and PSG0225 after BTS. As shown in Fig. 4.18, the C-V curve for both samples has a positive voltage shift after BTS. Both samples show electron injection behavior, while PSG0225 shows ion drift behavior at room temperature before BTS.
Fig. 4.17 C-V curve measured by sweeping towards different directions on (a) Cree1, (b) NO0219, (c) PSG0225 and (d) Cree 2.
Table 4.3 summarizes the oxide charge behavior of P5, Cree1, NO0219 and PSG0225. P5 and Cree1 were previously heated to 400°C for lifetime measurements before the oxide charge behavior study.

<table>
<thead>
<tr>
<th></th>
<th>Before BTS at room temperature</th>
<th>After BTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>P5</td>
<td>ion drift</td>
<td>ion drift</td>
</tr>
<tr>
<td>Cree1</td>
<td>ion drift</td>
<td>ion drift</td>
</tr>
<tr>
<td>NO0219</td>
<td>electron injection</td>
<td>electron injection</td>
</tr>
<tr>
<td>PSG0225</td>
<td>ion drift</td>
<td>electron injection</td>
</tr>
<tr>
<td>Cree2</td>
<td>no oxide charge behavior</td>
<td>NA</td>
</tr>
<tr>
<td>Cree3</td>
<td>electron injection</td>
<td>NA</td>
</tr>
</tbody>
</table>

Table 4.3. Oxide charge behavior before and after BTS.
We measured the conductance on NO0219 and Cree 3 which shows electron injection before and after BTS. Fig. 4.19 shows the conductance results for NO0219 before and after BTS under almost the same surface potential. As shown in Fig. 4.19, the interface response time does not change after BTS. Devices with electron injection behavior do not increase the $D_{it}$ extraction energy range after positive bias BTS as for devices with ion drift.

Fig. 4.20 shows the conductance results in the depletion region and the extracted $D_{it}$ profile for NO0219. As shown in Fig. 4.20(b), the extracted $D_{it}$ profile curve has a
discontinuous point between depletion and accumulation region. The discontinuity appears because the model we used only fits in the depletion region, not in the accumulation region.

Fig. 4.20. (a) Small signal ac interface state conductance $G_p/\omega$ as a function of $\omega$ in the depletion region on and (b) extracted $D_n$ profile for NO0219.

Fig. 4.21 shows the conductance results and extracted $D_n$ profile for Cree 3. Cree 3 is an unpassivated sample, as we expected, the extracted $D_n$ for Cree 3 is higher than any other sample we have measured.
Fig. 4.21. (a) Small signal ac interface state conductance $G_p/\omega$ as a function of $\omega$ and (b) extracted $D_{it}$ profile for Cree3.

Fig. 4.22 shows the conductance results and extracted $D_{it}$ profile using this parasitic reduction method compared with the $D_{it}$ result derived without using the parasitic reduction method for the samples NO0219. Fig. 4.22 only shows $G_p/\omega$ v.s. $\omega$ at one bias point because the data is too noisy to be able to distinguish between multiple bias point data in the same figure. As shown in Fig. 4.22(b), the $D_{it}$ result using the parasitic reduction method is only slightly higher than the result without using the parasitic reduction method.
Fig. 4.22. (a) Small signal ac interface state conductance $G_p/\omega$ as a function of $\omega$ at $\phi_s=0.09$ and (b) extracted $D_{it}$ profile with and without parasitic reduction for NO0219.

Fig. 4.23. Small signal ac interface state conductance $G_p/\omega$ as a function of $\omega$ scale to (a) low frequency peak, (b) high frequency peak for PSG225.
Fig. 4.23 shows the conductance results for PSG225. As shown Fig. 4.23(a), the conductance peak is at lower frequency and out of our measurement range. The fact that the peak is not fully accessible within the range of measurement frequencies makes it impossible to determine the $D_{it}$ value from the low frequency peak. However, there is a second peak at higher frequency with lower magnitude. In Fig. 4.23(b), the peak can be observed by changing the $G_D/\omega$ scale. We can fit the conductance curve to this higher frequency peak using Eq. (4.13) and extract the $D_{it}$ value. The $D_{it}$ profile extracted by curve fitting is shown in Fig. 4.24.

Fig. 4.24. extracted $D_{it}$ profile for PSG225.
Fig. 4.25 shows the conductance results and extracted $D_{it}$ profile for sample 142. Similar to PSG225, the conductance peak for sample 142 at lower frequency is out of our measurement range, but the sample exhibits another peak at higher frequency with lower magnitude as well. In Fig. 4.25(a), the high frequency peak can be observed by changing the $G_p/\omega$ scale. By fitting the conductance curve with Eq. (4.13) we can extract the $D_{it}$ value. The $D_{it}$ profile extracted by curve fitting is shown in Fig. 4.25(b). In case of sample 142 we can only extract the $D_{it}$ profile for a very small energy range due to the conductance peak being small and only measurable for a small range of voltage bias values.

![Graph depicting conductance results](image)

(a)

![Graph showing extracted $D_{it}$ profile](image)

(b)

Fig. 4.25 (a) Small signal ac interface state conductance $G_p/\omega$ as a function of $\omega$ and (b) extracted $D_{it}$ profile for 145.
4.5. High-low Frequency Capacitance Method on SiC MOS-C

For high-low frequency capacitance measurement, we used samples NO0219, PSG225 and 145. All of the samples listed in table 4.1 are n-type samples. In order to minimize the effect of gate leakage current, we selected the device on the samples which had the smallest gate leakage current for the high-low frequency capacitance measurement. The capacitance data were measured with a Keithley package 82 system.

The Keithley package 82 system is a computer-controlled system of instruments designed to simultaneously measure quasistatic and high frequency CV on semiconductors. Keithley package 82 system includes a Keithley model 590 CV analyzer for high-frequency CV measurements, a model 595 quasistatic CV meter along with the necessary input coupler and low noise cables. A model 230-1 voltage source providing the DC bias voltage is also included. The package 82 system is controlled by a LabVIEW program.

Fig.4.26 shows the extracted \( D_{it} \) profile from high-low frequency capacitance measurement, compared to a conductance measurement for sample NO0219. As shown in Fig.4.2+, the extracted \( D_{it} \) profile from the high-low frequency capacitance measurement is lower than the profile derived from the conductance measurement within the same energy range. This is due to the frequency limit of the Keithley package 82 system. With high frequency only being 100 kHz the frequency is not high enough so that some fast traps will still respond, resulting in underestimating the \( D_{it} \) value. However, the high-low frequency capacitance measurement technique allows us to extract the \( D_{it} \) profile for a larger energy range.
Fig. 4.26. Interface trapped charge density versus energy from the high-low frequency and conductance capacitance measurement on NO0219.

Fig. 4.27 shows the extracted $D_{it}$ profile from high-low frequency capacitance measurement and conductance measurement on PSG225. As shown in Fig.4.27, for the same reason, the extracted $D_{it}$ profile for the high-low frequency capacitance measurement is lower for the same energy range. Compare to NO0219, both high-low frequency capacitance measurement and conductance measurement technique show lower $D_{it}$ values.
Fig. 4.27. Interface trapped charge density versus energy from the high-low frequency and conductance capacitance measurement on PSG225.

Fig. 4.28 shows the extracted $D_{it}$ profile from high-low frequency capacitance measurement and conductance measurement on sample 145. As shown in Fig. 4.28, the extracted $D_{it}$ profile for the high-low frequency capacitance measurement is higher than the value derived from the conductance measurement. This can be explained by the high-low frequency capacitance measurement measuring the traps responding at lower frequencies that can be probed via the conductance measurement as indicated in Fig. 4.25(a).
Fig. 4.28. Interface trapped charge density versus energy from the high-low frequency and conductance capacitance measurement on 145.
5.1. Fast Interface States

In the last chapter, we introduced the origins of the interface states at the oxide/semiconductor interface, discussed the methods to measure interface state density $D_{it}$ used in this work and presented the measurement results obtained at room temperature or at elevated temperature. As mentioned in the first chapter, despite the progress in SiC device technology in recent years, the inversion channel mobility of 4H-SiC MOSFETs has been surprisingly low, still being much lower than the bulk mobility. The low inversion channel mobility of 4H-SiC MOSFETs has been suggested to be mainly due to the high density of interface states at the SiO$_2$/SiC interface [29]. As we discussed in chapter 3, the most common passivation method is to introduce nitrogen at the SiO$_2$/4H-SiC interface by using post-oxidation anneals in NO or N$_2$O [30]. Another nitridation method that limits the unwanted oxidation during NO annealing process is annealing in nitrogen plasma [52]. A lower $D_{it}$ value has been reported by using these nitrogen based passivation methods. However, in some cases, although the measured $D_{it}$ has been low, the effective channel mobility still remained low, contradicting the theory that the interface defect density is responsible for reduced channel mobility [31, 53].

It has been reported recently that increasing the nitrogen coverage at the interface during nitrogen post-oxidation annealing will potentially create additional fast interface states at the interface. These fast interface states have a shorter response time compared to
the conventional interface states. Due to the short response time of these states they are not detected by conventional $D_{\text{it}}$ characterization techniques and protocols. In this chapter, we conducted measurements on samples at temperatures down to 100K using both the high-low frequency and conductance methods. As we lower the measurement temperature, the time constant of the interface states increases, shifting the response frequency into the experimentally accessible measurement range, allowing us to evaluate the $D_{\text{it}}$ of the fast interface states. Assessing the samples at different temperatures enables characterization of the interface states at different energy levels. Similar to the analysis performed in the last chapter, the capture cross section of the fast interface states was extracted from the frequency of the peak conductance. The measurements were repeated on samples passivated with phosphorus to determine if PSG-SiO$_2$ also contains fast interface states.
5.2. Response Time of Interface States in Wide Bandgap Semiconductor

![Graph showing time constant for holes to emit from an interface state to the valence band in a p-type 4H-SiC. Capture cross section for holes is $10^{-15}$ cm$^2$. The horizontal lines indicate the frequency limitation of the Agilent 4294 impedance meter.]

In this section, we discuss the response time of the interface states in a silicon carbide MOS device. Response times of interface states increases exponentially with the energy from the band edge towards the middle of the bandgap. The response times of interface states deep in the bandgap can be extremely long in wide bandgap semiconductors such as...
silicon carbide. The time constant for an interface state to emit a hole to the valence band in a p-type semiconductor is given by [3]

\[
\tau_p(E) = \frac{1}{\sigma_p \nu_T N_V} \exp \left(\frac{E - E_V}{kT}\right)
\]

(5.1)

where \(\sigma_p\) is the capture cross section for holes, \(\nu_T\) is the electron thermal velocity, \(N_V\) is the valence band effective density-of-states, \(k\) is Boltzmann’s constant, \(T\) is the absolute temperature and \((E - E_V)\) is the energy of the interface state relative to the energy of the valence band edge.

The time constants for holes to emit from an interface state to the valence band in a p-type semiconductor for several temperatures are calculated with Eq. (5.1) and plotted in Fig. 5.1. The right-hand axis is the angular frequency corresponding to the interface state time constant. In Fig. 5.1, we assume that the interface state capture cross section for holes \(\sigma_p\) is constant throughout the entire bandgap, although \(\sigma_p\) has different values for different energies. Here we chose \(\sigma_p = 10^{-15}\ cm^2\), which is a reasonable number for Silicon MOS devices. The horizontal lines indicate the frequency limitation of the Agilent 4294A impedance meter.

In the past, in order to extract the conventional interface state density \(D_{it}\) for a wider energy range, people had to decrease the interface states response time by increasing the measurement temperature. Theoretically, we should be able to extract \(D_{it}\) throughout the entire bandgap by elevating the measurement temperature to 400 °C and measuring on both n-type and p-type samples. The capture cross section for both electrons \(\sigma_n\) and holes \(\sigma_p\) can also be extracted using n-type and p-type samples. As the result shown in the last
chapter, we are able to extract $D_{it}$ of our 4H-SiC samples for a wider range at room temperature due to the effect of the mobile ions in the oxide layer.

For measuring the fast interface states and extracting its $D_{it}$, instead of increasing the measurement temperature to decrease the interface state response time, we have to decrease the measurement temperature to increase response time of the fast interface states. Also, the capture cross section of the fast interface states can be extracted as well when the sample is cooled. More details of how to measure the fast interface states will be discussed later in this chapter.
5.3. **Measurements of Fast Interface States**

Before discussing how to measure the fast interface states, we first have to address some details of the sample preparation. The MOS capacitor samples investigated in this chapter were fabricated by Prof. Sarit Dhar of the Auburn University Physics Department. These MOS capacitor samples underwent the following interface passivation processes: (1) NO annealing (2) N plasma annealing (3) phosphosilicate glass (PSG) treatment. The basic ideas behind these three passivation processes have been discussed in chapter 3. A dry oxide layer was grown at 1150°C for the NO and PSG capacitor samples, the oxide thicknesses are ~60 nm. For the NO capacitor sample, following the oxidation process, nitric oxide annealing was performed at 1175°C for 2 hours. In case of the PSG capacitor samples, the oxides were annealed at 1000°C in N₂, which itself was bubbled through a POCl₃ bubbler maintained at 15°C. During this annealing, oxygen flowed simultaneously into the furnace tube. For comparison, there were two different POCl₃ annealing times were used: Sample ‘PSG11’ was annealed for 10 min and sample ‘PSG12’ for 15 min. For sample PSG11 and PSG12, the effective oxide thicknesses (EOT) were 61 nm and 70 nm respectively. The larger oxide thickness of PSG12 compared to PSG11 can be attributed to additional thickening of the oxide in POCl₃ [32]. Following the POCl₃ annealing, both PSG capacitor samples were annealed at 1000°C in pure N₂ (PSG11 for 30 minutes and PSG12 for 50 minutes). As for the N plasma process capacitor sample, first, a thin ~15 nm oxide layer has been formed by dry oxidation, then the sample was annealed in a N plasma annealing system at 1160°C for 4 hours. After the sample was annealed in N plasma, a TEOS-based LPCVD process was used to deposit additional oxide, the total oxide
thickness for the N plasma process capacitor sample is about ~60 nm. For all capacitor samples, molybdenum metal was sputtered for gate metallization and the contacts were defined using photolithography [54].

In this chapter, the samples were measured using an Agilent 4294A impedance analyzer for the conductance measurement and the Keithley system 82 for the high-low frequency capacitance method. Details of these two $D_{it}$ extraction method has been discussed in the last chapter. In order to measure the samples at low temperature, the samples were mounted inside a LakeShore cryostat LTS-21 with the measurement instruments connected to the device under test via coaxial cables wired into the chamber via SMA vacuum feedthroughs. The temperature was controlled by a LakeShore temperature controller DRC-84C. The samples were measured at different temperatures from room temperature to 100K [54].

For the conductance measurement, the frequency sweep from 40Hz to 10MHz at different gate voltages with a 25 mV small-signal voltage. The capacitance and conductance were measured at all measurement frequencies in strong accumulation to determine the parasitic correction. This admittance was then subtracted from measurements taken in depletion [44]. The interface state density $D_{it}$ and the interface state time constant $\tau$ have been extracted by fitting the experimental results with Eq. (4.13) [38, 42, 43]. For the samples studied in this chapter, the standard deviation of surface potential $\sigma$ ranges between values of 2.5 to 4. The energy level of the extracted interface state was calculated from the depletion layer capacitance using Eq. (4.14) and Eq. (4.15). The capture cross section $\sigma_e$ of the extracted interface state was calculated from $\tau$ by using Eq. (5.1). By
lowering the measurement temperature below room temperature, \( \tau \) increased, allowing the conductance peak to shift within the measurable frequency range [54].

For the high-low frequency capacitance method, the high frequency we used was 100 kHz. In our case, we can only extract the interface states that respond faster than the low-frequency signal and slower than the high-frequency signal [55]. Similar to the case of the conductance measurement, by lowering the measurement temperature, the fast responding interface state time constants can be shifted to lie in our accessible measurement range [54].

For of the MOS capacitor samples that underwent an NO anneal, a distinct peak in the \( G_p/\omega \) versus \( \omega \) plot was not observable at room temperature within the range of applied bias voltages. Biasing the MOS capacitor into strong accumulation did not cause a sufficient surface potential change that would result in a shift of the peak into the measurement frequency range. The fact that no distinct peak can be observed in the samples presented here can beinterpreted by the interface states either responding faster than the maximum or slower than the minimum measurement frequency. By lowering the measurement temperature, fast interface states can be slowed down in response, shifting them into the measurement frequency range. Fig. 5.2 plots the conductance \( G_p/\omega \) versus \( \omega \) at four different temperatures lower then room temperature. We first observed a \( G_p/\omega \) peak at 220K. By lowering the temperature further, we were able to observe more \( G_p/\omega \) peak which represents the interface states closer to the conduction band edge. As shown in Fig. 5.2, for the interface states closer to the conduction band edge, its \( G_p/\omega \) peak value is higher [54].
For the MOS capacitor samples that underwent a nitrogen-plasma anneal, we found similar results with the MOS capacitor samples that underwent an NO anneal. There is no $G_p/\omega$ peak could be observed at room temperature. Fig. 5.3 shows the conductance $G_p/\omega$ versus $\omega$ at different temperatures measured on the N-plasma sample. $G_p/\omega$ peaks were observed at 220 K, 180 K, 140 K and 100 K. Similar to the NO-annealed sample, the peaks
measured at lower temperatures exhibit a higher $G_p/\omega$ peak value and represent interface states close to the conduction band [54].

Fig. 5.3. The conductance $G_p/\omega$ versus $\omega$ at 220 K, 180 K, 140 K and 100 K measured on N-plasma passivated sample [54].
Fig. 5.4. Interface state density for NO and N-plasma sample extracted from the curves in Figs. 5.2 and 5.3 [54].
Fig. 5.5. The conductance $G_p/\omega$ versus $\omega$ at room temperature measured on sample (a) PSG11 and (b) PSG 12 [54].
Fig. 5.4 shows the extracted Dit values for NO and N-plasma samples. As shown in Fig. 5.4, the Dit values are very similar for the two different nitrogen-based passivation methods, with the N-plasma sample exhibiting a Dit that is slightly lower close to the conduction band edge [54].

For the MOS capacitor samples that underwent PSG passivation, contrary to the nitrogen passivated samples showed above, distinct peaks in the \( G_p/\omega \) versus \( \omega \) plot were observable at room temperature. Fig. 5.5 shows conductance \( G_p/\omega \) versus \( \omega \) at room temperature measured from PSG11 and PSG12. The interface states in the PSG samples could be detected at room temperature in our measured frequency range, suggesting that the interface states in the PSG passivated samples have a larger interface state time constant than the ones we measured in the nitrogen passivated samples. The curves in Fig. 5.5 represent interface states 0.2 to 0.3 eV below the conduction band edge. Further biasing into depletion moved the Fermi level deeper in the bandgap, resulting in the disappearance of a distinct peak in our measured frequency range due to the longer response time of the interface state deeper in the bandgap. The \( G_p/\omega \) peaks shown in Fig. 5.5 for the PSG samples are lower than in the nitrogen passivated samples at the same energy level (shown in Fig. 5.2 and Fig. 5.3). This suggests that the Dit value is lower for the PSG samples. Also, the PSG12 sample shows a lower \( G_p/\omega \) peak than the PSG11 sample at the same energy level, implying the PSG12 has a lower Dit value. As we lowered the measurement temperature, for both PSG11 and PSG12 sample, no distinct peak in the \( G_p/\omega \) versus \( \omega \) plot was observable within the range of applied bias voltages. This suggests that there are
no fast-responding interface states present the PSG/SiC interfaces, result in higher mobility for a PSG passivated sample [54].

Fig. 5.6. Observed interface state density for (a) NO, (b) N-plasma, (c) PSG11 and (d) PSG12 sample extracted from the conductance method and the high-low capacitance method [54].
The $D_{it}$ profile extracted from the NO- and N-plasma annealed samples as well as those from the PSG (PSG11 and PSG12) samples using both the conductance method and high-low frequency capacitance method are shown in Fig 5.6. For the NO and N-plasma passivated samples, the $D_{it}$ value derived from the high-low frequency capacitance method at room temperature has a higher value compared to the $D_{it}$ value derived from the conductance method for most of the measured energy range. As we lower the measurement temperature, the $D_{it}$ value derived from the high-low capacitance method starts to decrease and falls below the value obtained using the conductance method. The high-low capacitance method integrates the interface states with different time constants in the measured frequency range. Thus, the extracted data reflects the combination of different types of interface states. In case of the room temperature measurements, the high-low capacitance method has the ability to probe interface states that are too slow for the conductance method to detect, since the lowest measurement frequency of Agilent 4924A is 40 Hz. By lowering the measurement temperature the already slow time constant interface/near interface states will react even slower, eventually becoming too slow for the high-low method to be able to detect it, since the integration time of the quasistatic capacitance meter is finite as well. This causes the $D_{it}$ values derived from the high-low technique to decrease with temperature. On the other hand, lowering the measurement temperature will cause the fast time constant interface states to slow down to lie within our measurement frequency range. Thus, the $D_{it}$ values in Fig. 5.6 extracted from the conductance method at low temperatures represent the contribution of fast interface states [54].
As shown in Fig. 5.6, for samples PSG11 and PSG12, as we lower the measurement temperature, the \( D_{it} \) value derived from the high-low capacitance method decreases faster compared to the nitrogen passivated samples. This is due to the lack of fast interface states in the PSG passivated samples. At room temperature, the \( D_{it} \) value derived from the high-low capacitance method is much higher than the \( D_{it} \) value derived from the conductance method, this indicates that there are interface states which have a response times that are too slow for the conductance method to detect, but these slower interface states can be measured by the high-low capacitance method at room temperature. As we decrease the measurement temperature, these slow interface states will then become too slow for both the high-low capacitance method and the conductance method to detect. These results indicate that the higher channel mobility in PSG MOSFETs is due to a lower \( D_{it} \) value of fast interface states at the PSG/SiC interface. This is consistent with recent publication that reports the correlation between the channel mobility and the fast interface state in nitrogen passivated MOSFETs fabricated on a different crystal face of 4H-SiC [54].

Fig. 5.7 shows observed \( D_{it} \) extracted by high-low capacitance measurement at 300 K for the NO- and N-plasma annealed samples as well as those from the PSG PSG11 and PSG12 samples, the observed \( D_{it} \) value does not show much of a difference at room temperature [54].
Fig. 5.7. Comparison of observed interface state density for NO, N-plasma, PSG11 and PSG12 samples extracted by high-low frequency capacitance measurement at 300 K [54].

The interface state capture cross-section ($\sigma_c$) for the NO, N-plasma and PSG annealed samples are also extracted by using the conductance method. As shown in Fig. 5.8, $\sigma_c$ for the NO and N-plasma annealed samples has an exponential dependence on energy and ranges from $10^{-17}$ to $10^{-10}$ cm$^2$ in the measured energy. Such large values of $\sigma_c$ have also been reported by other gropes [35, 56]. For the PSG annealed samples, the extracted $\sigma_c$ value are in the lower $10^{-18}$ cm$^2$ range, which is much smaller compared to the values for
the nitrogen-based annealed samples in the same energy range. This indicates that the interface states which are measured by using the conductance method for the nitrogen-based annealed samples and the PSG annealed samples are different types of interface states [54].

![Graph showing capture cross-section for fast interface states in NO and N-plasma samples and regular states in PSG samples [54].](image)

Fig. 5.8. Capture cross-section for fast interface states in NO and N-plasma samples and regular states in PSG samples [54].
5.4. Conclusion

In this chapter, we have measured the interface state densities at the SiO$_2$/SiC interface from room temperature to 100K using both the conductance and the high-low frequency methods for various SiC MOS samples. These samples were passivated by two nitrogen-based techniques (NO and nitrogen-plasma) and the PSG technique. We have successfully measured and confirmed the existence of fast interface states in the SiC MOS samples which underwent nitrogen-based passivation, the $D_{it}$ profiles for these samples has been extracted by both conductance and high-low frequency measurements. On the other hand, no fast interface states were observed in PSG-passivated samples using the same characterization methods. However, conventional interface states with time constants similar to the interface states found in silicon samples have been observed at room temperature [54].

Based on our findings, there are two types of interface states present at the SiC/SiO$_2$ interface. These two types of interface states shows different energy dependencies of the capture cross section, this indicates that these two types of interface states have different origins. For the fast interface states, its capture cross section has an exponential dependence on energy, and for conventional interface states, the capture cross section does not show a clear dependence on energy. Furthermore, compared to the fast interface states, the conventional interface state density is several orders of magnitude smaller. Also, the interface states which have very long response times in all the samples can only be detected by the high-low frequency capacitance method but not by the conductance method [54].
CHAPTER 6. FUTURE WORK

6.1. Future work

In this work, we successfully measured the interface state density $D_{it}$ for various energy ranges for both n- and p-type substrate SiC MOS capacitors using the conductance measurement and the high-low frequency capacitance method under different conditions and protocols. The $D_{it}$ profile extracted from samples which underwent different passivation process has also been compared side by side for the purpose of determining the better passivation method. The presence of fast interface states has been confirmed and their $D_{it}$ profile has been extracted from the samples that underwent nitrogen based annealing processes. On the contrary, no fast interface state were found in the samples that underwent the PSG annealing. We also discovered the effect of mobile ions in the oxide layer on the response time of the interface states. Although this work helps us to understand some important features of a SiC MOS system, it also points out several topics that still cannot be fully explained. Thus additional work is required in order to understand and further resolve these topics. We list some of the topics and our suggestions on how to move forward:

1. It remains unclear where exactly the near-interface state are located in a SiC MOS device, i.e if these states are in the substrate or in the oxide layer close to the SiC/SiO$_2$ interface. The profile of these near-interface states can potentially be extracted by using deep-level transient spectroscopy (DLTS) and the charge pumping method. The challenge using these two methods is that both methods require a MOSFET structure to yield meaningful results. Thus, SiC MOSFET
samples need to be fabricated and characterized in the future. An introduction to
the DLTS technique is presented in the next section.

2. The origin and the chemical nature of the fast interface states remains largely
unknown. It has been suggested that nitrogen at the interface and the near interface
oxide will potentially increase the concentration of fast interface states. More work
has to be done to fully understand the nature of the fast interface states.

3. Interface states which respond slower than conventional interface states have also
been observed. In order to completely measure and extract the density profile,
different methods or protocols must be applied. Increasing the measurement
temperature and/or lowering the measurement frequency might allow us to obtain
the density profile of these slow interface states.

4. The nature of how mobile ions effect the response time of the interface state isn’t
fully understood yet. However, exploring this effect allows us to extract the $D_{it}$
profile for a much larger energy range and can potentially be used for other wide
bandgap materials in the future.

5. The lack of fast interface states in the samples that underwent PSG passivation leads
to higher field-effect mobility. Different dopants could be used in the future to
avoid creating fast interface states and potentially achieve higher field-effect
mobility and a more robust oxide layer.

6. By benefiting from advances in Si technology, other alternative insulators besides
$\text{SiO}_2$ could be employed within the SiC MOS system. For example, a high-k
dielectric on top of the native $\text{SiO}_2$ might achieve higher gate control and lower
gate leakage current.
6.2. Deep-Level Transient Spectroscopy

4.7.1 Conventional Deep-Level Transient Spectroscopy

Sah and his students developed the early C-t and I-t measurement and methods [57, 58]. The initial method were single-shot measurements, the measurement was time-consuming and tediously long. In 1974, Lang proposed the dual-gate integrator or boxcar approach named Deep-Level Transient Spectroscopy (DLTS), it was the first one among these DLTS techniques [59-61].

Fig. 6.1. Capacitance versus time at different temperature. t₁ and t₂ are the sampling time.

For this technique, the rate window concept was introduced to the deep level impurity characterization. Here we use the capacitance transients to explain DLTS. Assuming the C-t transient follows the exponential time dependence [27]
\[ C(t) = C_0 \left[ 1 - \frac{n_0}{2N_D} \exp \left( -\frac{t}{\tau_e} \right) \right] \]  \hspace{1cm} (6.1)

where \( C_0 \) is the capacitance of a device with no deep-level impurities at reverse bias, \( \tau_e \) depends on temperature as

\[ \tau_e = \frac{\exp((E_c-E_T)/kT)}{\gamma n \sigma n^2} \]  \hspace{1cm} (6.2)

When the temperature increases, the time constant \( \tau_e \) decreases, shown in Fig. 6.1.

During the measurement, the capacitance decay waveform is usually corrupted by noise, thus the ability to extract the signal from the noise in an automated manner is the core of DLTS. DLTS is a correlation technique, the correlator output is

\[ \delta C = \frac{1}{T} \int_0^T f(t)w(t)dt = \frac{1}{T} \int_0^T \left( 1 - \frac{n_0}{2N_D} \exp \left( -\frac{t}{\tau_e} \right) \right) w(t)dt \]  \hspace{1cm} (6.3)

where \( T \) is the period, \( w(t) \) is the weighting function and we use Eq. (6.1) for \( f(t) \).

For boxcar DLTS, the capacitance difference between \( t=t_1 \) and \( t=t_2 \) as shown in Fig 6.1 is a standard output feature of a double boxcar instrument, i.e. \( \delta C = C(t_1) - C(t_2) \). The device is pulsed between zero and reverse bias repetitively when the temperature is scanning slowly. At low and high temperature, there is almost no capacitance difference between \( t=t_1 \) and \( t=t_2 \) due to very slow and very fast transients. As you scan through the
temperature, capacitance difference $\delta C$ will pass through a maximum value as a function of temperature. By using $(t) = \delta(t - t_1) - \delta(t - t_2)$, Eq. (6.3) become

$$
\delta C = C(t_1) - C(t_2) = \frac{n \tau^{(0)}}{2N_D} C_0 \left( \exp\left(-\frac{t_2}{\tau_e}\right) - \exp\left(-\frac{t_1}{\tau_e}\right) \right)
$$

(6.4)

where $T = t_1 - t_2$ in Eq. (6.3).

The maximum capacitance difference $\delta C_{max}$ occurs at a particular temperature. By differentiating Eq. (4.37) with respect to time constant $\tau_e$ and setting the result to zero, we can get the maximum time constant $\tau_{e,\text{max}}$ at $\delta C_{\text{max}}$ as

$$
\tau_{e,\text{max}} = \frac{t_2 - t_1}{\ln(t_2/t_1)}
$$

(6.5)

The signal baseline does not need to be known, because in Eq. (6.5), $\tau_{e,\text{max}}$ is independent of the capacitance magnitude. For a given gate setting $t_1$ and $t_2$, we can generate a series of C-t curves at different temperatures and generate one value of $\tau_e$ corresponding to a particular temperature. This will give us one point on a $\ln \tau_e T^2$ versus $1/T$ plot. By changing to another gate setting $t_1$ and $t_2$ and a repeat of the measurement sequence, we can generate another point. After several times of repeating the sequence, we can obtain a series of points that allows us to generate an Arrhenius plot. Fig. 6.2 shows an example of the $\delta C$-t plot with the $t_2/t_1$ fixed for varies of $t_1$ and $t_2$ values.
Fig. 6.2. DLTS spectra for fixed $t_2/t_1$ and different $t_1$ and $t_2$. [27]

The signal to noise ratio is proportional to the square root of the gate width. In order to lower the noise, the gate width should be relatively wide [62]. Eq. (6.5) then needs to be modified to

$$
\tau_{e,max} = \frac{(t_2+\Delta t)-(t_1+\Delta t)}{\ln((t_2+\Delta t)/(t_1+\Delta t))}
$$

(6.6)

where $\Delta t$ is the gate width [63].

We can derive the impurity density from the maximum capacitance difference $\delta C_{max}$ of the C-t curves, with $\delta C_{max} = \delta C$, assuming $n_T(0) = N_T$. We can derive $N_T$ from Eq. (6.5) and Eq. (6.6)
\[ N_T = \frac{\delta C_{\text{max}}}{c_0} \frac{2N_D \exp\left(\frac{r}{(r-1)} \ln(r)\right)}{1-r} = \frac{\delta C_{\text{max}}}{c_0} \frac{2r^{r/(r-1)}}{1-r} N_D \]  

(6.7)

where \( r = t_2/t_1 \). \( r = 2 \) is a common ration for this measurement.

\[ \frac{\delta C_{\text{max}}}{c_0} \approx 10^{-5} \] can be detected by a DLTS system, allowing us to determine trap densities on the order of \( 10^{-5}N_D \). \( \frac{\delta C_{\text{max}}}{c_0} \) as low as \( 10^{-6} \) can be measured by a high-sensitivity bridge. Also, capacitance meters should feature modified response times in order to measure faster transients [64].

### 4.7.2 Interface Trapped Charge DLTS

Interface trapped charge DLTS employs identical instrumentation to what is used for bulk deep-level DLTS. Because interface traps have an energy distribution throughout the band gap and bulk traps have discrete energy levels, the data interpretation for interface trapped charge DLTS is different than bulk deep-level DLTS. Fig. 6.3 illustrates the concept of interface trapped charge majority carrier DLTS for the MOS capacitor. In Fig. 6.3 (b), electrons are captured and occupy the interface traps when a positive bias is applied. In Fig. 6.3 (c), electrons are emitted from the interface traps to the conduction band in deep depletion when a negative bias is applied. The emitted electrons will result in a capacitance, current or charge transient. The emission of the electrons from interface traps in the upper band gap will dominates, although electrons are emitted over a broad energy spectrum. DLTS is a very sensitive technique, it can measure the interface trap density on the order of \( 10^9 \text{ cm}^{-2}\text{eV}^{-1} \).
This technique was first implemented using MOFETs [65]. As a three terminal device, MOSFETs as a test device have an advantage over MOS capacitors as a test device. By reverse biasing the source and drain, minority holes will be collected by the source and drain and will not interfere with the majority electrons that are captured and emitted. This allows us to characterize the interface traps located in the upper band gap by majority electrons. Also, by forward biasing the source and drain and forming an inversion layer, the interface traps will be filled with minority holes. This allows us to characterize the interface traps located in the lower band gap by minority holes. Without source and drain, this is impossible to accomplish with just a MOS capacitor due to lack of a minority carrier...
source. The majority carrier interface trap DLTS measurements will be interfered within an inversion layer in MOS capacitor because of thermal electron-hole-pairs generation, especially under high temperature and high electron-hole-pairs generation rates.

Nevertheless, MOS capacitors were used for interface trap characterization [66, 67]. Interface trapped charge DLTS measurements are independent of surface potential fluctuations, unlike the conductance measurement discuss earlier. Compare to diodes, MOS capacitors require a more complex derivation of the capacitance expression. For $q^2D_{it} = C_{it} \ll C_{ox}$ and $\delta C = C_{hf}(t_1) - C_{hf}(t_2) \ll C_{hf}$ [27]

$$\delta C = \frac{C_{hf}^3}{K_S \varepsilon_0 N_D C_{ox}} \int_{-\infty}^{\infty} \bar{d} \delta x \left( e^{-t_2/\tau_e} - e^{-t_1/\tau_e} \right) dE_{it} \quad (6.8)$$

Where

$$\tau_e = \frac{e^{(E_C - E_{it})/kT}}{\gamma_n \sigma_n T^2} \quad (6.9)$$

$E_{it}$ is the energy of the interface traps. Eq. (6.5) gives us the maximum emission time for an interface trap, when $\tau_{e, max}$ corresponds to $E_{it, max}$, Eq. (6.9) become

$$E_{it, max} = E_C - kT \ln \left( \frac{\gamma_n \sigma_n T^2(t_2 - t_1)}{\ln(t_2/t_1)} \right) \quad (6.10)$$
where $E_{it,\text{max}}$ is a sharp peak. In Eq. (6.10), the electron capture cross-section is not a strong function of energy. In Eq. (4.41), $D_{it}$ can be considered as a constant if the $D_n$ value changes slowly in a few kT energy range around $E_{it,\text{max}}$. $D_n$ can be then taken outside of the integral and the remaining integral will become

$$
\int_{-\infty}^{\infty} \left( e^{-t_2/\tau_e} - e^{-t_1/\tau_e} \right) dE_{it} = -kT \ln(t_2/t_1)
$$

(6.11)

and Eq. (6.8) becomes

$$
\delta C \approx -\frac{c_{hf}^2}{K_s\varepsilon_0 N_D C_{ox}} kT D_{it} \ln(t_2/t_1)
$$

(6.12)

From Eq. (6.12), $D_{it}$ is

$$
D_{it} = -\frac{K_s\varepsilon_0 N_D C_{ox}}{kT c_{hf}^3 \ln(t_2/t_1)} \delta C
$$

(6.13)

Eq. (6.13) is determined by the interface trap emitted electrons in time $\Delta t$ in the energy interval $\Delta E = kT \ln(t_2/t_1)$ at $E_{it,\text{max}}$. By varying $t_1$ and $t_2$, we can plot $D_{it}$ versus energy. For a chosen $t_1$ and $t_2$ set, $D_{it}$ and $E_{it}$ can be obtained from Eq. (6.13) and Eq. (6.9). For samples containing both interface and bulk traps, we can distinguish interface traps from the bulk traps by the shape and the peak temperature of the DLTS plot [68].
Constant capacitance DLTS is another DLTS technique that has been used to measure interface traps [69]. For constant capacitance DLTS,

\[
D_{it} = \frac{c_{ox}}{qkTA \ln(t_2/t_1)} \Delta V_G
\]  

(6.14)

where \(A\) is the device area and \(\Delta V_G\) is the value of how much the gate voltage has to be changed to maintain a constant capacitance. Compared to Eq. (6.13), Eq. (6.14) is easier to use because there is no high-frequency capacitance and doping density needed to derive \(D_{it}\).
References


