A comparison of free carrier absorption and capacitance voltage methods for interface traps measurements

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Abstract

This project aims at establishing a new method to characterize the interface between 4H-SiC and passivating dielectric layers. The investigations are made on metal-oxide-semiconductor (MOS) test structures. The oxides are made of Al₂O₃, deposited by atomic layer deposition (ALD), and SiO₂, deposited by plasma-enhanced chemical vapour deposition (PECVD) and the semiconductor is lowly doped 4H-SiC n-type epitaxial layers. These structures have been exposed to different fluencies of Ar ion irradiation to induce damage at the interface and then measured by well-established electrical techniques, as well as the new method utilizing optical free carrier absorption (FCA) technique to assess the interface traps.

We have furthermore developed an analytical tool using Matlab that can extract surface recombination velocity (SRV) from the optical data. This tool is developed for an idealized epi-layer between two surfaces, but could also be applied, for instance, to the region between the emitter and base contacts on SiC mesa etched BJT’s. First, optical free carrier absorption (FCA) measurements are carried out to measure the effective lifetimes in the structures. The data obtained from FCA is then fitted with the analytical tool and SRVs, for samples with both types of dielectrics with various Ar ion fluencies, are extracted. Standard electrical measurements using capacitance-voltage (CV) measurements are also undertaken and the density of interface traps (Dᵣ) is extracted using the Terman method. Extracted SRV values are then compared to Dᵣ values.

It is observed that SiO₂ samples show a large rise of SRVs, from 0.5×10⁴ cm/s for a reference sample to 8×10⁴ cm/s for a fluence of 1×10¹² cm⁻², whereas Al₂O₃ samples show more stable SRV, changing from 3×10⁴ cm/s for the un-irradiated reference sample to 6×10⁴ cm/s for a fluence of 1×10¹² cm⁻². A very similar trend is observed for Dᵣ values extracted from CV measurements and it can therefore be concluded that the FCA method is very suitable for characterization of the interface, and together with CV, it should be possible to obtain quantitative values on charge carrier trapping dynamics.
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Chapter 1

Introduction

One of the key components which revolutionized the way we live now is the wide range of transistors, which is heart of all the electronic gadgets. So, the power consumption of these gadgets is determined by the transistors used in them. The demand for the electricity is increasing dramatically day to day. International Energy agency (IEA) has estimated that the worldwide energy consumption will increase two folds only from last decade to this decade [1]. This has raised an alarming issue of carbon foot prints on environmental changes. It is furthermore reported that 33% of the power generated in USA is wasted and the 15-20% of this can be saved by effective implementation of power electronics [2]. New semiconductor devices are therefore needed for a more efficient use of electric power.

Ever since the beginning of the electronics age, silicon has established its dominance over the other semiconducting materials because of its availability, processing capability, etc., but by the end of 1980s it was realized that silicon power devices were approaching its theoretical limitation [3]. Instead a new, wide bandgap, semiconductor silicon carbide (SiC) has evolved as a contender for high power applications. For instance, the specific on resistance ($R_{sp}$) for the drift region in a power semiconductor device is given by

$$R_{sp} \propto \frac{V_b^2}{E_c^3} \quad \ldots \ldots \quad (1)$$

where critical electric field for breakdown is ($E_c$), and the blocking voltage is ($V_b$) It is known that the critical electric field for breakdown ($E_c$) for SiC is 2.2 MV/cm whereas for Si is 0.3 MV/cm [3]. From these values and the equation (1) it can be said that for the same blocking voltage, the SiC devices will have considerably lower specific resistance. So, an effective implementation of this material in power devices contributes to large reduction in power losses. SiC has today about 3% of the power device market. These devices have an energy saving compared to what is generated by 20 coal power stations thus contributing to huge reduction in carbon footprints and a cleaner environment.

This thesis addresses one of the remaining major issues with SiC power devices, namely the reliability of the dielectric and SiC interface. The dielectric material and the
interface to SiC need to be improved, not only for the implementation of MOSFET transistors, but also for improving surface passivation of other device areas exposed to high electric fields. For instance, the performance of SiC BJT is degraded by carrier recombination in the side walls of Emitter/Base interface. One of the problems with this interface is surface states mainly related to the remaining carbon atoms or clusters at these interfaces [4, 5]. These surface states trap the carriers which contribute to the low current gain thus degrading the BJTs [4, 5].

Since SiO$_2$ is a natural oxide of SiC this would have been the first choice of material as dielectric. But still MOS structures using SiC/SiO$_2$ are not yet fully commercialized, because of the poor interface quality, enabling for instance Fowler-Nordheim (FN) tunnelling mechanism which allows tunnelling of carriers into SiO$_2$ [4]. However, a lot of research is being done to improve the interface between SiC and SiO$_2$ but also other materials are being investigated. Researchers in the recent past years have shown that Al$_2$O$_3$ can be a good candidate for replacing SiO$_2$ [6, 7].

This thesis aims at investigating the influence of ion radiation of MOS capacitors and the effect on their electronic properties. In this MOS test structures there are two types of oxides (Al$_2$O$_3$ and SiO$_2$) which are exposed to different Argon implantations. The primary point of focus is to evaluate a new way of measuring the interface properties using an optical technique called free carrier absorption. We have developed an analytical tool for extracting Surface Recombination Velocities (SRV) for FCA technique. In addition we tried to make an comparison of how the SRVs extracted from the optical measurements correlate with the density of interface traps deduced from the electrical measurements.

The content of this thesis is depicted in the following way Chapter 2 describes the basic material physics and properties of SiC, SiO$_2$, Al$_2$O$_3$. Chapter 3 covers the experimental details including the sample fabrication process along with the parameters used for ion implantation. Chapter 4 deals with the experimental setup and measurement techniques of both optical characterization, using Free Carrier Absorption measurement, and electrical Capacitance Voltage measurements. Chapter 5 briefs about the analytical model developed for an idealized epilayer between two surfaces to extract these Surface Recombination Velocities (SRV) from the Free Carrier Absorption (FCA) measurement. In chapter 6 the results are analysed in detail and reported. First, the data obtained from FCA is fitted with the analytical tool and SRVs for samples with both types of dielectrics have been extracted.
Then, electrical measurements using a capacitance-voltage (CV) probe station are also undertaken and the density of interface traps ($D_{it}$) are extracted using the Terman method. Finally, an investigation for the results extracted from the optical and electrical measurements is made.
Chapter 2

Basic Semiconducting Physics and Material properties

This chapter deals with some fundamental concepts of semiconducting physics associated with the semiconductor/dielectric interface and carrier trapping and detrapping. But first, some material properties focusing on SiC, Al₂O₃, and SiO₂ will be discussed.

2.1. Basic Material Properties

2.1.1 Properties of Silicon Carbide

One of the properties of SiC crystals is the ability to grow with different stacking in repetition frequencies, so called polymorphism. There are over 150 polytypes of SiC, but only three of these types are in use for electronic devices because of their superior electronic properties and the availability [8, 9]. The crystalline structures of these three polytypes are as shown in Fig 2.1. These different polytypes in SiC are mainly due to the periodicity of Si-C atoms in the c-direction [10].

![Diagram of different SiC polytypes](image)

Fig.2.1. Three form SiC available which are key structures for electronic industry [11]
3C-SiC as a cubic Zinc Blend crystalline structure and this is the only one cubic polytype of SiC. The stacking of 3C-SiC is of the form ABCABC... as it can be observed from Fig 2.1.a. This is also called as α-SiC. The other two crystals 4H-SiC and 6H-SiC are hexagonal (wurtzite) structure and their atomic stacking is ABACAB... and ABCACBABC... respectively. These are also called as β-SiC [12, 10]. The 4H-SiC consists of 50% of cubic and 50% of hexagonal lattice sites, whereas 6H-SiC consist of 1/3 of cubic and 2/3 of hexagonal lattice sites [1].

2.1.2. Properties of Silicon Dioxide

SiO₂ is one of the special dielectrics when it comes to electronics industry since it is a natural oxide for Si and so is with SiC.. The relative dielectric constant of SiO₂ is 3.9 with a bandgap of 9 eV which gives rise to an offset of 2.7 eV with respect to the conduction band of 4H-SiC. SiO₂ have a breakdown voltage about 10 MV/cm and a thermal conductivity of about 0.015 W/cmK [10]. The most commonly used techniques for the deposition of SiO₂ is Chemical Vapor Deposition, Plasma Enhanced chemical Vapor Deposition, liquid phase chemical Vapor Deposition and Atomic Layer Deposition [10].

2.1.3. Properties of Aluminum Oxide

Aluminum Oxide has captured the device researchers in the recent past because of the following properties: It as a wide bandgap in comparison with SiO₂ which is 8.8 eV and a high potential barrier to Si which is 2.8 eV. The band offset with 4H-SiC is about 1.7 eV which is effective to stop the carrier injection [10]. It has a breakdown voltage greater than 5 MV/cm and a thermal conductivity of about 0.02 W/cmK [10]. Its crystalline form is called Sapphire or α- Al₂O₃ and it has a rhombohedral structure. The growth of crystalline form of the Al₂O₃ on SiC is demanding, as there is a large lattice mismatch [10]. But the amorphous form can be a fascinating material to investigate as a dielectric. Al₂O₃ can be grown by different techniques such as sputtering, plasma deposition, thermal oxidation of AlN, atomic layer deposition (ALD) and ultrasonic spray pyrolysis [10]. In this thesis, all the samples are grown using ALD technique.

2.2. Carrier Recombination Process in 4H-SiC

Carrier recombination is a process where an electron and a hole combine with each other either across the bandgap or from the band edge to a level within the bandgap. In this process both the carriers are eliminated. This thesis focuses on 4H-SiC which has an indirect
band gap. The phenomenon of recombination in these types of materials is known as non-radiative recombination and there are two main types observed in 4H-SiC. These are Sockhley Read Hall (SRH) recombination, dominantly observed below a carrier concentration of below $10^{17}$ cm$^{-3}$ and Auger recombination dominating above $10^{18}$ cm$^{-3}$ [13].

2.2.1. Bulk Recombination

This type of recombination depends on crystal defects, introduced during the fabrication process. As a result of these imperfections they may form allowed energy level deep in the forbidden bandgap. These traps are termed with the label $E_t$, and they are much important since they act as R-G centers.

Fig 2.2. shows two ways to envisage how this type of recombination takes place. The first way is an electron falls from the conduction band ($E_c$) to the mid band trap states ($E_t$) and from there this electron jumps to a hole in valence band ($E_v$). A second view is that both charge carriers from their respective energy bands jump to the trap energy level and recombine [17]. This recombination occurs in both low and high level injections.

2.2.2. Surface Recombination:

The surface recombination refers to the processes where carriers are generated or recombinde at the surface or interface. Fig 2.3. shows the basic carrier capture and emission mechanism due to the surface traps. The surface recombination is in principal the same as bylk SRH, but the formalism differs due to two aspects. Firstly the energy levels are not discrete but tend to be distributed in the bandgap because of the much larger variations of bond formation available. Secondly, the recombination occurs in a plane rather than a volume.
This is the reason why we have to introduce the surface recombination velocities (SRV) as a parameter. The defects are one of the crucial parameters which often degrades the performance of the devices. Hence by surface passivating the device using apt material will reduce these defects [17].

2.2.1. Auger Recombination:

This type of recombination becomes dominant when the carrier injection level is high since it requires 3 particles to participate, 2holes+1electron or 2 electrons+ 1 hole. As shown in Fig 2.4, when an e-h pair recombines a certain energy is given up. This energy is absorbed by a carrier nearby, so that it is excited to higher energy levels. These are generally represented as e-e-h or h-h-e where the last two signifies the e-h recombination and the first letter characterizes the excited carrier or the auger carrier [17]. It is shown that this recombination process can be very significant in 4H-SiC at a concentration of $10^{18}$ cm$^{-3}$ [13].
2.3. Traps in SiC/Dielectric Interface:

In this section we would concisely look at the traps formed at the SiC and dielectrics interface primarily focusing on SiO$_2$ and Al$_2$O$_3$ on 4H-SiC.

2.3.1 SiC/SiO$_2$ Interface:

When it comes to SiC/Dielectric interface the first choice would be SiO$_2$ as it is the only natural oxide of SiC.

Fig 2.5 shows the schematic representation of SiC/SiO$_2$ [18]. This interface with respect to the position of the trap energies can be broadly divided into 3 regions, namely SiC/SiO$_2$ interface, SiC near interface, SiO$_2$ near interface. It can be observed that the SiC has a larger bandgap in comparison with Si and thus most of these defects are well within the conduction and valence band of the Si thus making these defects ineffective in this material [18]. The SiC interface is predominantly occupied by carbon clusters and these carbon atoms are $\Pi$-bonds which are covalently bonded. These $\Pi$-bonds are found to be electrically active and they either behave as donors if they are 0 to 3.6 eV below conduction band and as acceptors when they are localized below [18].
As mentioned above the SiC/SiO\textsubscript{2} interface is divided into 3 regions and SiO\textsubscript{2} near interface is in turn classified into near interface traps and slow oxide traps as shown in Fig 2.5. This was first reported by Afanasev et al [14].

Near interface traps: these are acceptor like traps which are confined at 2.8 eV at the SiO\textsubscript{2} conduction band and are fast traps. They are likely to contribute to the degradation of channel mobility chiefly for the reason of fast trapping and high concentration [14, 18].

Slow oxide traps: The origin, trap energies and their charges are not yet clear and many researchers are investigating these types of traps using electric characterization technique. They degrade the MOS stability which has adverse effect on its gate control [14, 18].

2.3.2. SiC/Al\textsubscript{2}O\textsubscript{3} Interface:

As mentioned in the chapter one of the limitations of SiC in power devices is to find a dielectric which has good interfacial properties. SiO\textsubscript{2} grown by thermal oxidation shows density interface traps (Dits) as high as $10^{14}$ cm\textsuperscript{-2}eV\textsuperscript{-1}.This results in a decrease of free carriers available for charge transportation and increase the on-state resistance. One of the possible ways to improve SiC/dielectric interface is to replace SiO\textsubscript{2} with Al\textsubscript{2}O\textsubscript{3} grown with atomic layer deposition technique [12, 6, 7].

In this technique the Al\textsubscript{2}O\textsubscript{3} is deposited at low temperatures at around 300° C and this lowers the oxidation rate of SiC thus avoiding the formation of carbon clusters, resulting in a reduction of the Dits. T. Seyller et al have investigated the interface between the SiC/Al\textsubscript{2}O\textsubscript{3} grown by ALD and they found that the oxidation of the SiC is minimal and this makes the interface abrupt [12]. They also found that the H-terminated SiC/Al\textsubscript{2}O\textsubscript{3} interface has very less D\textsubscript{it}s in comparison with SiC/SiO\textsubscript{2} [12].
Chapter 3

Sample Description

This chapter introduces one of the newer methods for fabricating structures at atomic levels namely Atomic Layer Deposition. It will also describe the process involved in fabricating the MOS structures with Al$_2$O$_3$ and SiO$_2$ as dielectrics and Al as contact. Also the parameters used for ion implantation are mentioned.

3.1. Atomic Layer Deposition Technique

Atomic Layer Deposition (ALD) is a technique to achieve single atomic layers. In contrast to Physical Vapor Deposition (PVD) a technique utilized to deposit SiO$_2$, in ALD the growth is done in discrete processes. The technique consists of chemical precursor vapors, which are sequentially sprayed on the substrate in steps. Each step involves many surface interactions between the different precursors and the substrate occurs. The underpinning factor of this technique is that each step is self-limiting, i.e., once an atomic layer is grown the growth process stops itself. Thus, by controlling the parameters such as pressure, gas flow, temperature and number of cycles, different stacks can be achieved [22].

The key advantages of ALD over other deposition techniques are control of dielectric thickness at atomic level, uniform and smooth coating, conformality, growth at low temperature and low stresses in the grown layers. ALD also provides excellent adhesion due the strong chemical bonding at the first level. This deposition is also suited for the sensitive substrates, deep inside pores, trenches and cavities [22].

3.2. Fabrication process of MOS structures

The test structures are grown on 4° off-axis 4H-SiC wafers purchased form SiCrystal AG. After the surface treatment, a nitrogen doped n-type epilayer, of about 8-10 μm was grown. The doping concentration in epilayer is about $5\times10^{15}$ cm$^{-3}$. The surface roughness in epi-surface was found by AFM to be about 3 nm. The samples were then cleaned by standard cleaning procedure and finally dipped in HF solution to remove the native oxide [6].
3.2.1. Dielectric and Back Contact Deposition

After completion of the above process these samples were divided into two batches for formation of the dielectric layers using Al$_2$O$_3$ and SiO$_2$. The first batch was used for SiO$_2$. This deposition is done using Plasma Enhanced Chemical Vapor Deposition (PECVD), which is one of most effective method for forming the SiO$_2$. A layer of SiO$_2$ is deposited on SiC at 300 $^\circ$C. This process is then followed by N$_2$O annealing for 60 min at a temperature of 1150 $^\circ$C to obtain a high quality SiO$_2$. Using ellipsometry it was found that the thickness of the grown oxide was 54 nm [6,15].

The second batch was used for the deposition of Al$_2$O$_3$ structures using ALD. Here the precursors used are pure water (H$_2$O) and Trimethylaluminum (Al(CH$_3$)$_3$-TMA). This deposition process to obtain Al$_2$O$_3$ is done at a temperature of 300$^\circ$C [6, 15]. The basic deposition process is done in accordance to the following half reactions shown below [23]:

\[
\begin{align*}
\text{(Reaction A)} & \quad \text{Al-OH}^* + \text{Al(CH$_3$)$_3$} \rightarrow \text{Al-O-Al(CH$_3$)$_2$}* + \text{CH}_4 \\
\text{(Reaction B)} & \quad \text{Al-CH$_3$}* + \text{H}_2\text{O} \rightarrow \text{Al-OH}^* + \text{CH}_4
\end{align*}
\]

The asterix(*) represents the surface species. When these chemical reactions are performed in a sequence of ABAB..., and by charge balancing the Al-OH, a uniform and well controlled layer of Al$_2$O$_3$ is obtained. The thickness of this layer is about 56 nm. Once the dielectrics have been deposited, a 200 nm layer of Nickel is deposited, followed by rapid thermal annealing (RTA) of the wafer in Ar environment at a temperature of 950 $^\circ$C to obtain a silicide [6, 15]. Fig 3.1. shows the schematic flow of each process from surface treatment to back contact deposition. Note, when it comes to Al$_2$O$_3$ as dielectric the back contact is formed first and then followed by dielectric deposition using ALD.
3.2.2. Ion Implantation

The samples have been implanted with 50 keV argon ions using a fluence range from $1 \times 10^9$ to $10^{13}$ cm$^{-2}$. Fig 3.2. shows the schematic damage created in the sample due to ion implantation. In order to approximate the projected range of implanted ions, SRIM simulations [24] have been used. Using SRIM it has been assessed that the 50 keV Ar ions stop around the interface and, as it reaches the projected range, it makes maximum displacement damage due to elastic scattering. It is found that the ratio of nuclear stopping to stopping electronic was about 11, showing the dominance to the displacement damage [15].
After the ion implantation, the contacts are deposited. Here a 100 nm thick Al is used. The contacts are deposited in various contact sizes from 100 to 300 μm diameter [15].

### 3.2.3. Lithography

Lithography is one of the key processes in the fabrication process of semiconducting devices. Fig 3.3 shows schematically the flow of the lithography process for formation of contacts. Once the deposition of the Al layer is done, we spin coat a positive photoresist. The wafer is then soft baked at 90 °C for 90 sec and exposed to the UV-light with a mask aligned with the wafer. The wafer is then developed using a solvent which is generally basic in nature. This process removes the photoresist which is exposed to the by the UV-light. Then the wafer is hard baked at 110 °C for 5 min to make the remaining photoresist hard. Once the hard baking is done the wafer is examined in the microscope.

#### 3.2.4. Al top contacts etch and resist removal

Once the lithography is done our next task is to etch first the Al and then the remaining photoresist. Fig 3.4. shows the schematic flow of the etching process. The Al layer is etched using a wet etching process. The advantage with this process is the good selectivity and anisotropy. The samples are then ready for measurements.
Figure 3.4. Schematic flow of Al and Resist etching
Chapter 4

Measurement techniques

In this chapter we look into the experimental setup and data acquisition for both free carrier absorption (FCA technique), which is an optical measurement and capacitance voltage (CV), which is an electrical measurement.

4.1. Free carrier absorption

In order to establish effective lifetimes in the structures after various radiation exposures, optical free carrier absorption (FCA) measurements have been utilized. These effective lifetime values can then be used to extract recombination velocity of charge carriers at the interface between the epitaxial layer and the oxide. We have used the pump-probe beam setup in the laser lab at Electrum KTH, ICT to carry out these experiments.

4.1.1. Experimental Setup

Fig.4.1. Schematic view of Pump-Probe Setup used for FCA measurements [25]
FCA is an efficient technique to study lifetime of charge carriers in semiconductors. Fig 4.1. shows the principal of the pump-probe setup that was utilized to carry out the FCA measurements. The setup consist of four key components which are labelled as A,B,C,D in the figure shown above.

A) A pump laser with a wavelength of 355 nm, which is used to excite charge carriers in the sample.

B) A probe laser with a wavelength of the 861 nm which is a continuous beam laser. This light is absorbed by free charge carriers and by studying the amount of light transmitted through the sample it is used to study the decay of the excess charge.

C) A sample holder to which the sample is fixed. Both the probe and the pump laser are focused on to this with the help of various lenses. The movement of this holder is controlled by the computer, thus the angle at which these beams strike the sample can be controlled, as well as the spot on the sample.

D) A photodetector is placed behind the sample which is used to monitor the variations in the probe laser. The detector output is connected to an oscilloscope.

The pump laser wavelength intensity of 355 nm corresponds to the bandgap of SiC, which is 3.25 eV, is generated using Q-switched Nd:YAG laser, the output has a constant energy of 13 μJ per pulse. Half width of the pump laser is 2 ns with a spot diameter of 500 μm and a repetition rate of 40 Hz. This beam is then guided by a series of lenses and mirrors to produce a local excitation or carriers in the sample.

The probe beam is continuous and has a wavelength of 861 nm with 40 mW power. This wavelength is in the range of infra-red. The measurements are done under parallel geometry, where both pump and probe beam enter the sample in the same direction. An avalanche photo detector is behind the sample to measure the amount of probe beam absorbed by these excited carriers. This works on the basic principal of photo-detectors where the incoming light is converted to electricity by the photoelectric effect. The output of the detector is connected to a 2 GHz oscilloscope. This is in turn connected to a computer which records the intensities of absorbed probe beam vs time. This information can be converted to the excited charge carrier generated using the relation:

\[ \Delta n(t) = \left( \frac{1}{d\sigma_{\text{FCA}}} \right) \ln \left( \frac{I_0}{I(t)} \right) \]
Where $I_0$ and $I(t)$ are the incident and transmitted intensities respectively, $\sigma_{\text{FCA}}$ is the free carrier absorption cross section, $\Delta n(t)$ is excited carrier density and $d$ is distance in the sample.

### 4.1.2. Measurement Technique

The basic principal behind FCA is that the excited charge carriers absorb certain photons with energy below the bandgap of the material. These excited charge carriers are generated by illuminating the sample with energy above the bandgap. As shown in Fig 4.2, the former is done by the probe beam and latter by the pump beam [25].

![Diagram of FCA probing technique](image)

In this process when the pump beam is incident on the sample single package of photons from this light annihilates the electron or hole to higher states from conduction or valence band respectively and then relaxes back to intial state. Thus no excess carriers are generated in the sample. Therefore the efficiency of the system is proportional to the instantaneous concentration of excited carriers [25].
4.3.1. Data Acquisition

Using this FCA technique we could obtain the amount of light absorbed by the excited charge carriers. Fig 4.3. shows the how absorbed part (Transmitted)of the probe for SiO$_2$ on SiC sample with an Ar flunee of 1×10$^{10}$ cm$^{-2}$. This plot of absorption versus time consist of three regions described below:

A) This is the fast decay tail which corresponds to the thick SiC substrate. Here we have short lifetime corresponding to the fast recombination of minority charge carriers.

B) The second part corresponds to the epilayer which has an intermediate decay rate. From the slope of this part one can extract the effective lifetimes of the epilayer; this is the focus of investigation in this thesis.

C) The third part is the slow decay tail that relates to the impurities in the bulk. These have a longer lifetimes and could be neglected. After sufficiently long times the absorption/carrier concentration reaches steady state equilibrium values.

4.2. Electrical Measurements

In this thesis we have used capacitance voltage (CV) measurements to determine the density of interface traps (D$^i$). It is a fast and accurate technique used extensively to determine the electronic parameters of semiconducting devices. A detailed explanation of the basic physics for this measurement can be found in ref authored by Dieter K. Schroder[27].
4.2.1. Experimental Setup

In order to do these measurements we have utilized the probe station setup at KTH Electrum lab. Fig 4.4. shows the experimental setup for the CV measurement. First, the samples are placed on the chuck, which could be heated to carry high temperature measurements. There are four micro-positioned sharp needles which act as an electrical contact for the samples to be measured. These measurements are light sensitive and thus the probe station is designed in a way that no light enters to the measuring part. There is a microscope to adjust the contact of the micro tips with the sample. This probe station is then connected to a impedance analyzer LCR meter (HP 4284A) which in turn is connected to a computer. The entire measurement is controlled a Lab View program which is operated from the computer.

4.2.2. Non ideal effects due to Oxide

It has been recognized that four general types of charges are associated with the Dielectric/semiconductor interface, as shown in Fig 4.5. These charges are responsible for the non-ideal effects in MOS structures.
A) Mobile ionic charge ($Q_m$) that are due to ionic impurities such as Li$^+$, Na$^+$ and K$^+$ etc.

B) Oxide trapped charges ($Q_{ot}$) that are due to trapping of electrons or holes in the bulk of the oxide. This trapping may be caused by ionizing radiation or avalanche injection. Presence of these charges make a shift in the CV curves either in positive or negative voltage direction for negative/positive charges with respect to its ideal curve.

C) Fixed charges ($Q_f$) which arise due to structural defects of the oxide layer. The density of such charges is associated with the oxidation process. The presence of these charges causes a hysteresis loop in CV curves when it is swept from accumulation to inversion and back.

D) Interface trapped charge ($Q_{it}$) which are located at the dielectric/semiconductor interface. They are either positive or negative depending on their location with respect to Fermi level. They arise due to broken bonds, oxidation-induced defects, structural disorder, or defects caused by radiation. Presence of this charge makes the slope of the CV curves in the depletion and deep depletion regions vary in comparison with the ideal curves.
4.2.3. Terman Method

The Terman method is used to determine $D_{it}$ for the high frequency capacitance measurement. Here, the frequencies corresponding to the capacitance versus bias are at high enough value, so these $D_{it}$ do not have time to respond to the small signal ac voltage used for measuring capacitance. In this method the ideal curve, which is plotted for a normalised $C/C_{ox}$ versus surface potential, is compared with the experimental curve plotted as $C/C_{ox}$ versus gate voltage to extract the $D_{it}$ see Fig 4.6. Then these plots are compared with each other in order to obtain the $\psi_s$ of ideal CV and $V$ of the experimental curve corresponding to the same $C/C_{ox}$, as shown in Fig 4.6.a. The resulting $\psi_s$ versus $V$ is then plotted as shown in Fig 4.6.b. Using this plot the slope of this graph $d\psi_s/dV_g$ is extracted. The amount of $D_{it}$ are finally determined using the relation below [27]. Coding used to compute this equation is as shown in Appendix 4.

$$D_{it} = \left(\frac{C_{ox}}{q^2}\right)(dV_g/d\psi_s-1)-(C_D/q^2)$$
Chapter 5

Modelling of Carrier Lifetime for FCA technique

This chapter elucidates an analytical tool that is developed to extract these Surface Recombination Velocities (SRV) from the measurements using an optical technique called Free Carrier Absorption (FCA). The model is developed for an idealized epilayer between two surfaces as shown in Fig 5.1. This case has, however, strong resemblance with realistic cases, for instance in the base of a SiC BJT.

Fig 5.1 shows the simulated structure. Here the middle area (sample) represents the epilayer and the two blue surfaces represent the interface regions each with a specific SRVs. The following values have been assumed for the parameters in this simulation: doping of the sample is $10^{18}$ cm$^{-3}$, thickness of the sample is 400 μm, diffusion coefficient of the material is 15 cm$^2$/s and lifetime of the carriers is taken as 0.5 μsec. The thickness of the sample used in this chapter is two orders of magnitude larger practical epilayer used in FCA measurements. This is taken so in order to study the effect of various parameters in bulk of the semiconductor as well. But, the thickness of the sample was taken as 10 μm to extract the SRVs from FCA measurements. The surface recombination velocities (SRV) at both the edges are not confined to a fixed value since the goal is to extract this value for different passivation layers.

This report initially shows an analytical solution for the 1D diffusion equation and the behaviour of excess carriers. Then a numerical model is made by integrating bulk
recombination, diffusion and the surface recombination model to simulate the idealized physical situation.

5.1 Bulk recombination model

Bulk recombination is one of the key parameter in determining the carrier lifetime. Once the carriers are excited using the FCA technique these carriers will recombine. An analytical solution, which consist of just the bulk recombination, is presented in this section. In the analytical solution we assume that initial carriers \( n_0 \) are negligible as the generated carriers \( (\Delta n_0) \) using FCA is very large compared to \( n_0 \). Note that the unit of carrier concentration throughout these section is in \( \mu m^{-3} \), time is in \( \mu s \) and distance in \( \mu m \). The analytical solution is as shown below. Please refer to Appendix 1 for the full derivation.

\[
n(x,t) = n_0 e^{-x/(\tau D)^{1/2}} \text{erfc}(x/2t^{1/2}(\tau/4D)^{1/4}) ----1
\]

Where \( n_0 \) = initial carriers; \( \tau \) = carrier lifetime; \( D \) = diffusion coefficient; \( x \) = length of the device; \( t \) = time; \( n(x,t) \) = concentration of the carriers.

The above equation shows the concentration of the carriers that diffuse in the bulk of the device. Fig.5.2. corresponds to the behaviour of the excess carriers in the length of the device and is the graphical representation of the analytical solution as shown in Eq.1. Here the concentration of the carriers is in \( \mu m^{-3} \) and the distance of the device is in \( \mu m \).

Then a numerical simulation of the bulk recombination using the Matlab [28] has been carried out in order to verify our analytical model. The coding is as shown in Appendix 2. The variation of the concentration of electrons with respect to distance, which is the length of the device, is as shown in Fig.5.2, was found to be the same in both the analytical and numerical solutions. From the above solution it can be observed that bulk recombination depends on three factors which are 1) the diffusion constant, 2) recombination lifetime of the carriers and 3) the length of the device.
5.2. Integration of Bulk and surface recombination models

This module includes both the bulk and surface recombination which represents better the physical situation. Surface recombination is primarily due to the interface states at the surface the epilayer. These interface traps are distributed continuously throughout the bandgap and there is an energy dependence. In this simulation we have analysed the interface traps that are pinned at the Fermi energy. In this model we have considered that initially there are $10^{18}\text{ cm}^{-3}$ carriers in the sample. And there are surface traps at the both ends of the sample and the boundary condition we used is as shown below. The coding for the integrated module is shown in Appendix 3.

On left edge: $D \frac{dn}{dx} = S_1 \cdot n(l) \quad 2$

On right edge: $D \frac{dn}{dx} = -S_2 \cdot n(r) \quad 3$

Where $D =$ diffusion coefficient, $S_1 =$ surface velocity at left edge, $S_2 =$ surface velocity at right edge, $n(l) =$ carrier conc. at left edge, $n(r) =$ carrier conc. at right edge.

5.2. Results and Discussions

From the above numerical solution we have seen that the carrier decay mainly depends on the three parameters the surface recombination velocities at left and right edges, bulk lifetime and diffusion coefficient of the material. In the following sections we have used an integrated
surface, diffusion and bulk recombination model and have shown how the above mentioned parameters influences the carrier lifetime.

5.3.1. **Carriers decay when $S_1=S_2$**

The surface interface traps plays an important role for determining the overall lifetime of the sample. Fig 5.3. shows the concentration of carriers with respect to distance and time. Here the SRV at both the edges are considered to be same i.e. $S_1=S_2=10^6$ cm/s. So, the carriers start decaying at both edges which is due to the surface traps and after a certain time they reach a steady value where bulk recombination starts to reduce the whole distribution. The decay at the edges is symmetric due to the same SRV condition.

5.3.2. **Carriers Decay when $S_1>S_2$**

Fig 5.4. shows the carrier decay for the case where the SRV at the left edge is greater than that of the right edge. Here the value of $S_1$ is taken has $10^6$ cm/s and $S_2$ is taken has $10^5$ cm/s, so, the decay of the carriers at the left edge is very dominant over the right edge. This scenario represents a practical case of an epilayer where one edge as much fewer defects at one of the interface compared to the other.
5.3.3. Carriers Decay at Different Bulk Lifetimes

Fig. 5.5. shows the variation of concentration of carriers with distance of the sample for different bulk lifetimes at a 2 μs from the start of decay. Both edges are considered to be similar ($S_1=S_2$) and the diffusion coefficient is taken as 15 cm$^2$/s. As we can see the decay of carriers is faster for the shorter lifetimes since they recombine very rapidly. A big variation is
observed between 0.5 μs and 10 μs, whereas there was not much variation in concentration from 10 μs to 100 μs. This is mainly because of the exponential dependency of the bulk lifetime with respect to concentration.

5.3.4. Carriers Decay at Different Diffusion Coefficient

Fig. 5.6. shows the variation of concentration of carriers with respect to distance for different diffusion coefficient of the material. This simulation is done for the symmetric edges at 2 μs for a lifetime of 0.5 μs. The change in diffusion coefficient causes strong changes close to the surfaces. This suggests that the diffusion coefficient play an important role for the surface recombination by making carriers quicker to the surfaces.
Chapter 6

Results and Discussions

In this chapter the results are reported and analysed in detail. The data obtained from FCA is fitted with the analytical tool and SRVs for samples with both types of dielectrics have been extracted. Then, the densities of interface traps (D_a) are extracted from CV measurements using the Terman method. Finally, comparison of the results extracted from the optical and electrical measurements is made.

6.1. Extraction of SRV from Optical Measurements

Initially, the free carrier absorption measurements are done as explained in chapter 4 and the data for variation of absorption of probe light with respect to time is extracted. This gives a measure of the effective lifetime in the test structures. These effective lifetimes are then utilized to extract SRV of the epitaxial-oxide layer. So, in order to establish these SRVs the analytical tool, explained in chapter 5, was used by fitting the data obtained from measurements with the analytical tool. These measurements were done on 25-30 different spots on each sample and all these data have been averaged to get the final data corresponding to each sample.

As we have seen in section 5.3 there are four parameters involved in the analytical tool written in Matlab which are to be varied to fit with the measured data for SRV extraction. These parameters are lifetime (τ (μs)), Diffusion coefficient (D (cm²/s)), SRV of the epitaxial- substrate interface (S_l (cm/s)) and SRV of epitaxial- oxide interface (S_r (cm/s)). Our primary focus is to extract SRV of epitaxial- oxide interface (S_r). In order to do so, the remaining parameters have to be pinned at certain values. The following sections explain how these fittings are made.
6.1.1. Fitting the diffusion coefficient

First, an investigation of how the plots generated using the Matlab program with different D was done. Fig 6.1. shows the data fitting for the sample SiO$_2$ as dielectric with an Argon dose of $1\times10^{12}$. It can be seen that the entire dynamics of the plot in all three regions are strongly affected by the choice of D. Another inference from Fig.6.1. is that as D increases the fast decay tail corresponding to the substrate reduces i.e. the charge carriers recombine faster. This is in good agreement in theory. Now, in order to extract the SRV of the epitaxial-oxide interface the value of D has to be fixed. So, for the further simulations in this thesis we have used D=3 cm$^2$/s [13].

6.1.2. Fitting the epilayer lifetime

The next parameter which affects the data fitting is the carrier lifetime in the epitaxial layer. Fig 6.2. shows the fits for different lifetime for two samples where Fig 6.2.A., Fig 6.2.B. correspond to Al$_2$O$_3$ and SiO$_2$ as dielectric for $1\times10^{10}$ cm$^{-2}$/dose, respectively. In this simulation the lifetimes have been varied from 0.2 μs to 10 μs and it could be observed that this fit does not show much of variations from 0.5 μs and higher. It is the range between 0.1 μs to 0.5 μs which has a major effect on the curves and subsequently on the SRV of epitaxial-oxide. So, in the further fitting process we have used the lifetime between 0.1 μs to 0.5 μs in order to extract the $S_r$. 
Fig. 6.2. Curve fitting for different lifetime varied from 0.2μs to 10μs. A) corresponds to Al₂O₃ as dielectric with 1E10 dose. B) corresponds to SiO₂ as dielectric with 1E10 dose.
6.1.3. Variation of $\tau$, $S_l$ and $S_r$ for Reference fit

Once the diffusion coefficient and the lifetime has been optimized, we then tried to make reference fits by varying $\tau$, $S_l$ and $S_r$ so that curves of analytical tool exactly fits with that of measured data. Fig.6.3. shows the reference fit for Al$_2$O$_3$ as dielectric for no irradiation with $S_l = 3.7 \times 10^4$ cm/s, $S_r = 1 \times 10^3$ cm/s and $\tau = 0.12$ $\mu$s.

![Graph showing reference fit for Al$_2$O$_3$ dielectric](image)

Table 6.1. shows the parameters $S_l$, $S_r$ and $\tau$ for various samples with Al$_2$O$_3$ and SiO$_2$. Two observations can be made from the table. First, the SRV at the left edge ($S_l$), which corresponds to the epitaxial layer-substrate interface, is almost constant for all the samples with different dielectrics and dose. This is reasonable because for all the samples we have the same epi layer, which is n-type, and substrate (4H-SiC). The average trend of $S_l$ observed from Table 6.1. is about $4 \times 10^3$ cm/s. So, $S_l$ can be pinned to this value. Secondly, the test structure with SiO$_2$ as dielectric has an average lifetime of about 0.7 $\mu$s, whereas for Al$_2$O$_3$ as dielectric has only an average lifetime of about 0.2 $\mu$s. But in order to make a relative comparison of both these dielectrics test structures one need to fix the value of $\tau$, and we have taken a mean value between both the dielectrics which is 0.5 $\mu$s. This is a reasonable value for these samples and also higher bulk lifetimes do not affect the carrier dynamics where the other parameter starts dominating.
6.1.4. Extraction of $S_r$ with other parameters pinned

Using the above steps we have fixed the values of $D=3 \text{ cm}^2/\text{s}$, $S_l=4 \times 10^4 \text{ cm/s}$ and $\tau=0.5 \times 10^{-6} \text{ s}$. The final task is to extract the SRV of epi-oxide layer interface ($S_r$) for test structures with different dielectrics and dose. Fig.6.4. shows the curve fitting for extracting $S_r$.
with other parameters pinned for two samples where Fig 6.4.A., Fig 6.4.B. correspond to Al$_2$O$_3$ and SiO$_2$ as dielectric for $1 \times 10^{12}$ cm$^{-2}$ dose respectively.

A) Sample Al$_2$O$_3$/SiC 1E12; Extraction of SRV(right) for SRV(left)=0.4E5cm/s; lifetime=0.5E-6s, D=3cm$^2$/s

B) Sample Nr.4 SiO$_2$/SiC 1E12; Extraction of SRV(right) for SRV(left)=0.4E5cm/s; D=3cm$^2$/s, lifetime=0.5E-6s

Fig.6.4. Extraction of SRV of epi-oxide layer with other parameters pinned. A) corresponds to Al$_2$O$_3$ as dielectric with 1E12 dose. B) corresponds to SiO$_2$ as dielectric with 1E12 dose.

Table 6.2. shows the values of the SRV extracted by fixing the other parameters for the test Structures with Al$_2$O$_3$ and SiO$_2$ as dielectric. Fig 6.5. shows a comparison between epi-oxide SRV for test structures with different dielectrics and Ar dose.
It could be inferred that the SRV of the epi-oxide layer with SiO₂ as dielectric has a low value of $5 \times 10^3$ cm/s compared to that of Al₂O₃ which is $3 \times 10^4$ cm/s for the unirradiated sample. This suggests that the initial interface of SiO₂ has a better quality than Al₂O₃. But a sudden rise in SRVs is observed from $1 \times 10^{10}$ cm² dose for SiO₂ dielectric structure. On the other hand Al₂O₃ samples have shown more stable SRVs from the unirradiated sample until the $1 \times 10^{12}$ cm² dose. The peak value of SRV for Al₂O₃ and SiO₂ structures was observed at $1 \times 10^{12}$ cm² dose which is $6 \times 10^4$ cm/s and $8 \times 10^4$ cm/s, respectively. This suggests that

<table>
<thead>
<tr>
<th>Sample</th>
<th>SRV at left edge($p_l$) cm/s *10⁵</th>
<th>SRV at right edge($p_r$) cm/s *10⁴</th>
<th>Life Time($\tau$) Ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF</td>
<td>0.4</td>
<td>3</td>
<td>0.5</td>
</tr>
<tr>
<td>1e10</td>
<td>0.4</td>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>1e11</td>
<td>0.4</td>
<td>6</td>
<td>0.5</td>
</tr>
<tr>
<td>5e11</td>
<td>0.4</td>
<td>5.5</td>
<td>0.5</td>
</tr>
<tr>
<td>1e12</td>
<td>0.4</td>
<td>6</td>
<td>0.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sample</th>
<th>SRV at left edge($p_l$) cm/s *10⁵</th>
<th>SRV at right edge($p_r$) cm/s *10⁴</th>
<th>Life Time($\tau$) Ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>REF</td>
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<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>1e9</td>
<td>0.4</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>1e10</td>
<td>0.4</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>1e11</td>
<td>0.4</td>
<td>5</td>
<td>0.5</td>
</tr>
<tr>
<td>1e12</td>
<td>0.4</td>
<td>8</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 6.2. Extraction of $S_r$ with other parameters fixed for various samples of Al₂O₃ and SiO₂ as dielectrics.
devices with Al₂O₃ as dielectric is a better choice for radiation rich environment. One more observation that could be made from Fig.6.5. for the SiO₂ structure is that the SRV is reduces for the Ar implantation of 1×10^{12} cm², suggesting that the implantation could improve the defect density of the structure. But in order to make conclusive statements, more investigations have to be done.

![Graph showing comparison of Surface Recombination Velocities extracted from FCA](image)

Fig.6.5. comparison between epi-oxide SRV for test structures with Al₂O₃ and SiO₂ as dielectric for various Ar implantations.

### 6.2. Extraction of DᵢᵣS from CV Measurements

Electrical measurements using a CV probe station are undertaken in order to find the number of Dᵢᵣ at the epi-oxide interface. We have used one of the high frequency methods called Terman method to extract Dᵢᵣ from CV measurements. Due to presences of Dᵢᵣ, a non-parallel shift of the CV-curves is seen stretching the slope of the CV curves in the depletion region. This technique makes a comparison of the amount of stretching encountered in the measured CV curves to that of the ideal curve. The coding for this technique is as shown in Appendix 4. The CV measurements have been made at different frequencies ranging from 1 khz to 1 Mhz with contact point of 100 μm, 200 μm and 300 μm. Fig 6.6. shows the CV measurements and the Dᵢᵣ extracted from the Terman method. Fig 6.6.B) and D) correspond to the CV measurements for Al₂O₃ for 1×10^{12} cm² and SiO₂ for 1×10^{9} cm² dose at different frequencies for a 200 μm in diameter contact point, Fig 6.6.A) and B) correspond to Dᵢᵣ values extracted using Terman method for Al₂O₃ and SiO₂ respectively.
It was not possible to extract the $D_{it}$ for the sample with SiO$_2$ dielectric for fluence above $5 \times 10^{11}$ eV$^{-1}$ cm$^{-2}$ since the CV curves never reaches accumulation in these region. This is shown in Fig.6.7. Another observation that could be made is that the CV curves for Al$_2$O$_3$ are shifted to positive voltage, which suggests that there are negative oxide charges, while the CV curves for SiO$_2$ samples shifts towards negative voltage, suggesting presents of positive oxide charges. Table 6.3. shows the values of $D_{it}$ extracted for various frequencies and fluence range for 200 μm contacts for Al$_2$O$_3$ and SiO$_2$, respectively.
Table 6.3. Extraction of Dit for various frequencies and fluencies for the 200μm contacts for samples with Al₂O₃ and SiO₂ as dielectrics.

<table>
<thead>
<tr>
<th>Sample dose</th>
<th>Contact size (μm)</th>
<th>1khz</th>
<th>10khz</th>
<th>100khz</th>
<th>1Mhz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref</td>
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<td>4.5×10¹¹</td>
<td>5.1×10¹¹</td>
<td>5.8×10¹¹</td>
<td>9.8×10¹¹</td>
</tr>
<tr>
<td>1E9</td>
<td>200</td>
<td>2.1×10¹¹</td>
<td>2.4×10¹¹</td>
<td>2.9×10¹¹</td>
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</tr>
<tr>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1E12</td>
<td>200</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Fig.6.7. CV measurements of SiO₂ for 110¹² dose at different frequencies on 200 μm contact showing the difficulty of extracting Dits using Terman method.
6.3. Correlating SRV and Dit from FCA and CV measurement

An important question is to see how the Surface Recombination Velocities (SRV) extracted from FCA measurements correlates with density interface traps (Dits) extracted from CV measurements. Fig 6.8. A) and B) shows the correlation of SRV and Dit for SiO₂ and Al₂O₃, respectively for various implanted Ar dose. In order to do this comparison the values of SRVs and Dits have been normalised. For the normalization we have taken CV measurements at 100 kHz for 200 μm contact and it could be observed that both the SRV and Dits follow same trend. But, same trend was observed for CV measurements at different frequencies and contact points. This gives a suggestion that the simulation presented in this thesis is an effective tool to extract the values of SRVs from FCA technique.

<table>
<thead>
<tr>
<th>Sample dose</th>
<th>Contact size (μm)</th>
<th>1khz</th>
<th>10khz</th>
<th>100khz</th>
<th>1Mhz</th>
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<tbody>
<tr>
<td>Ref</td>
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<td>2.4×10¹²</td>
<td>2.3×10¹²</td>
<td>4.9×10¹²</td>
</tr>
<tr>
<td>1E11</td>
<td>200</td>
<td>2.7×10¹²</td>
<td>3.0×10¹²</td>
<td>3.2×10¹²</td>
<td>8.0×10¹²</td>
</tr>
<tr>
<td>1E12</td>
<td>200</td>
<td>2.2×10¹²</td>
<td>2.1×10¹²</td>
<td>2.5×10¹²</td>
<td>6.9×10¹²</td>
</tr>
</tbody>
</table>
Fig. 6.8. Correlation between SRV and Dits A) for test structures with SiO$_2$ as dielectric for various Ar implantations. B) for test structures with Al$_2$O$_3$ as dielectric for various Ar implantations.
Chapter 7

Conclusion

In this thesis we have presented a new method to characterize the interface of 4H-SiC and passivation dielectric layer. These investigations were made on two passivation dielectrics which are Al$_2$O$_3$ and SiO$_2$. The optical free carrier absorption technique (FCA) and electrical Capacitance Voltage (CV) measurements are utilized for the characterization.

First we have developed an analytical tool using Matlab by which it is possible to extract the surface recombination velocities (SRV) at the interface by fitting to the data obtained from FCA measurements. It was observed that for unimplanted sample SRV of SiO$_2$ sample was $0.5 \times 10^4$ cm/s which are lower in comparison to that of Al$_2$O$_3$, which is $3 \times 10^4$ cm/s. But at a fluence of $1 \times 10^{10}$ cm$^{-2}$ there was huge rise in the SRVs of SiO$_2$, which peaked at $8 \times 10^4$ cm/s for a fluence of $1 \times 10^{12}$ cm$^{-2}$. Al$_2$O$_3$ samples showed more stable SRVs distribution over entire fluence range with the highest value of $6 \times 10^4$ cm/s for $1 \times 10^{12}$ cm$^{-2}$ fluence. The density of interface traps ($D_{it}$) are extracted using the Terman method from electrical capacitance-voltage (CV) measurements. The highest $D_{it}$’s was observed for SiO$_2$ samples with $9.5 \times 10^{11}$ cm$^{-2}$ at $1 \times 10^{11}$ cm$^{-2}$ fluence, whereas, for Al$_2$O$_3$ samples it was $2.5 \times 10^{11}$ cm$^{-2}$ at $1 \times 10^{12}$ fluence cm$^{-2}$.

It was observed that both SRVs and $D_{it}$’s had a very good correlation. Thus this shows the usefulness of FCA method to study the interface. It could be concluded that with FCA measurements together with CV measurements one can obtain quantitative values of charge carrier trapping dynamics.

The data also suggests that Al$_2$O$_3$ is better choice of dielectric for devices in radiation rich application.

In the future, these samples can be annealed and the same techniques can be used to investigate the effect of annealing on the SRVs and Dits at the interface. It would be also interesting to do IV characterization to study the leakage currents in these samples before and after annealing.
Appendix 1

Analytical solution

Consider the 1D diffusion equation which takes into account just the bulk recombination and
the generation is neglected and is given by 1.

\[ \frac{\partial n}{\partial t} = D \frac{\partial^2 n}{\partial x^2} - \frac{n}{\tau_n} \quad \text{-------- 1} \]

Where the \( n \) is the carriers that diffuse \((\text{cm}^3)\), \( D \) is the diffusion co-efficient of the
material \((\text{cm}^2/\text{s})\), \( x \) is the length of the device, \( \Delta n \) is the excess charges that are produced by
illumination \((\text{cm}^3)\), \( \tau_n \) \((\text{s})\) is the bulk lifetime if the carriers and \( t \) is the time taken \((\text{s})\).

Generally the total charge carriers in the device is given by

\[ n = n_0 + \Delta n \]

Where \( n_0 \) are the initial carriers that are present before illumination, and \( \Delta n \) is the
excess charges that are produced by illumination.

In this analysis we assume that \( n_0 \ll \Delta n \), so we will have \( n = \Delta n \). Sub this in equ 1.

\[ \frac{\partial n}{\partial t} = D \frac{\partial^2 n}{\partial x^2} - \frac{n}{\tau_n} \quad \text{-------- 2} \]

This is a second order differential equation and in order to solve these some assumptions
must be made.

Let us assume \( \overline{n}(p) = \int_0^\infty e^{-pt} f(t) \, dt \)

Where \( p \) is a constant and \( t \) is the time \((\mu\text{s})\). Multiply \( e^{-pt} \) to equ 2 and integrate them on both
sides

\[ \int_0^\infty e^{-pt} \frac{\partial n}{\partial t} \, dt = D \int_0^\infty e^{-pt} \frac{\partial^2 n}{\partial x^2} \, dt - \int_0^\infty e^{-pt} \frac{n}{\tau_n} \, dt \]

\[ \frac{\partial^2 \overline{n}}{\partial x^2} = \left[ \frac{p}{D} + \frac{1}{\tau D} \right] \overline{n} \]

\[ \overline{n} = \frac{n_s}{p} e^{-\frac{p + \frac{1}{\tau D}}{2} x} \quad \text{-------- 3} \]
Where \( n_s \) is the initial carrier concentration that are present in the device before the probe measurement is about to be done.

By expanding binomially the exponential term

\[
(Pr+1)^{1/2} = 1 + Pr/2 - (Pr)^{2/2.4} + \ldots
\]

Neglecting higher order terms since \( \tau \) is itself a very small value.

\[
= 1 + Pr/2
\]

Substituting the above expression in 3

\[
\bar{n} = \frac{n_s}{p} e^{-\frac{Pr+1}{\sqrt{D\tau}}} x
\]

Taking inverse fourier

\[
n(x,t) = n_s e^{-\sqrt{t(D)}} \text{erfc}(x/2t^{1/2} (\tau/4D)^{1/4}) \ldots 4
\]

The above equation shows the concentration of the carriers that diffuse in the bulk of the device. Fig.A.1. corresponds to the behaviour of the excess carriers in the length of the device and is the graphical representation of the analytical solution as shown in Eq.1. Here the concentration of the carriers is in \( \mu m^{-3} \) and the distance of the device is in \( \mu m \).
Appendix 2

Coding for the Bulk recombination

function [c,f,s] = pdex1pde(x,t,u,DuDx)
c = 1;
f = 15*10^8*DuDx;
s = -(u/(0.5e-6));
end

function [pl,ql,pr,qr] = pdex1bc(xl,ul,xr,ur,t)
pl = ul-((10^6);
ql = 0;
pr = ur;
qr =0;
end

function u0 = pdex1ic(x)
u0 = zeros(size(x));
u0(1)=1;
end

function p
m = 0;
x = linspace(0,400,20)
t = linspace(0,2,5);
sol = pdepe(m,@pdex1pde,@pdex1ic,@pdex1bc,x,t);
u = sol(:,:,1);
surf(x,t,u)
title('Numerical solution computed with 20 mesh points.')
xlabel('Distance x')
ylabel('Time t')
figure (2)
hold on
plot(x,u(:,;))
title('Diffusion Model')
xlabel('distance')
ylabel('u(x,2)')
end

This coding consists of four functions in total as shown above. Each of these functions has a specific mathematic representation associated with them. The first function (pdx1pde(x,t,u,DuDx)) is used to define the partial differential equation. The second function (pdx1bc(xl,ul,xr,ur,t)) describes the boundary condition of the PDE. Here in this analysis two edges which are the right boundary (ur) and the left boundary (ul) and they are fixed with a constant on each ends. The third function (pdx1ic(x)) is the initial boundary condition, here in our analysis there is not any initial effect and therefore we assign it to zero. The fourth function (p) is used to call all three functions together in order to solve the PDE and the resulting solutions are graphically represented.
Appendix 3

Coding for idealized epilayer between two surfaces

function \([c,f,s] = \text{pdex1pde}(x,t,u,DuDx)\)
\[c = 1;\]
\[f = 15*10^8*DuDx;\]
\[s = -(u/(0.5e-6));\]
end

function \([pl,ql,pr,qr] = \text{pdex1bc}(xl,ul,xr,ur,t)\)
\[pl = -10^6*ul;\]
\[ql = 20;\]
\[pr = 10^6*ur;\]
\[qr = 20;\]
end

function \(u0 = \text{pdex1ic}(x)\)
\[u0 = \text{zeros(size(x));}\]
\[u0(1)=10^{18};\]
end

function \(p\)
\[m = 0;\]
\[x = \text{linspace}(0,400*10^{-4},100)\]
\[t = \text{linspace}(0,5*10^{-6},5);\]
\[sol = \text{pdepe}(m,@pdex1pde,@pdex1ic,@pdex1bc,x,t);\]
\[u = \text{sol}(:,:,1);\]
\[\text{surf}(x,t,u)\]
\[\text{title}('Numerical solution computed with 20 mesh points.\:')\]
\[\text{xlabel}('Distance } x\text{')}\]
\[\text{ylabel}('Time } t\text{')}\]
\[\text{figure (2)\]
\[\text{hold on}\]
plot(x,u(2,:))
hold on
title('With surface recombination S1=S2')
xlabel('distance (cm)')
ylabel('n(x,t)(cm^-3)')
figure (3)
hold on
plot(t,u(:,:))
title('with surface recombination')
xlabel('Time in micro sec')
ylabel('u(x,t)')
end

The coding for the integrated module is as shown above. This module is similar to the bulk recombination except for the boundary condition. In the bulk we have consider the edges to be fixed with certain concentration and see how the carrier decay. Whereas in this model the edges are with surface interface traps and the boundary condition for this condition is as show in equation 2,3 in chapter 5. In the coding the function (pdex1bc(xl,ul,xr,ur,t)) corresponds to the boundary condition of the PDE. This function has two similar parts (pr, qr/pl, ql) which represents the right and left edges respectively. The term qr denotes coefficient of the first order differential term and the pr denotes the constant term in the equation 3.
Appendix 4

Coding for extracting $D_{its}$ using Terman method

%to compute CV curves
figure (1)
r1=data(1,4);
c1=data(:,4)/data(1,4);
plot((-data(:,3)),c1,'g');
hold on
r2=data(1,6);
c2=data(:,6)/data(1,6);
plot((-data(:,5)),c2,'r');
hold on
r3=data(1,8);
c3=data(:,8)/data(1,8);
plot((-data(:,7)),c3,'c');
hold on
r4=data(1,10);
c4=data(:,10)/data(1,10);
plot((-data(:,9)),c4,'k');
hold on
plot(data(:,1),data(:,2));
title('SiO$_2$/SiC 1E9 200micrometer CV-Curves')
xlabel('Gate Voltage(V)')
ylabel('C/C0')
legend('1Khz','1Mhz','10Khz','100Khz','Ideal curve')
% compares the slope of ideal and measured curves for given C/Cox
for i=4:1:9;
b=4;
c=(i-b)+1
u=i/10;
a=[-30,u;30,u];
x4=a(:,1);
y4=a(:,2);
x1=-data(:,3);
y1=c1;
x2=-data(:,5);
y2=c2;
x3=data(:,1);
y3=data(:,2);
x5=-data(:,7);
y5=c3;
x6=-data(:,9);
y6=c4;
[X1(c),Y1(c)]=curveintersect(x1,y1,x4,y4);
[X2(c),Y2(c)]=curveintersect(x2,y2,x4,y4);
[X3(c),Y3(c)]=curveintersect(x3,y3,x4,y4);
[X4(c),Y4(c)]=curveintersect(x5,y5,x4,y4);
[X5(c),Y5(c)]=curveintersect(x6,y6,x4,y4);
end

cs1=r1/(3.14E-4);
co1=r1/(3.14E-4);

cs2=r2/(3.14E-4);
co2=r2/(3.14E-4);

cs3=r3/(3.14E-4);
co3=r3/(3.14E-4);

cs4=r4/(3.14E-4);
co4=r4/(3.14E-4);

q=1.602e-19;
% to formulate the Dits
for r=1:1:5  
D1(r)=(X3(r+1)-X3(r))/(X1(r+1)-X1(r));  
cit1(r)=(co1*((1/D1(r)-1))-cs1;  
dit1(r)=cit1(r)/q;  
end  
dit_1k=mean(abs(dit1))  

for r=1:1:5  
D2(r)=(X3(r+1)-X3(r))/(X2(r+1)-X2(r));  
cit2(r)=(co2*((1/D2(r)-1))-cs2;  
dit2(r)=cit2(r)/q;  
end  
dit_1M=mean(abs(dit2))  

for r=1:1:5  
D3(r)=(X3(r+1)-X3(r))/(X4(r+1)-X4(r));  
cit3(r)=(co3*((1/D3(r)-1))-cs3;  
dit3(r)=cit3(r)/q;  
end  
dit_10K=mean(abs(dit3))  

for r=1:1:5  
D4(r)=(X3(r+1)-X3(r))/(X5(r+1)-X5(r));  
cit4(r)=(co4*((1/D4(r)-1))-cs4;  
dit4(r)=cit4(r)/q;  
end  
dit_100K=mean(abs(dit4))  

% to plot the Dits as a function of gate voltage  
figure (2)  
plot(X1(1:5),abs(dit1),'g')  
hold on  
plot(X1(1:5),abs(dit2),'r')
hold on
plot(X1(1:5),abs(dit3),'c')
hold on
plot(X1(1:5),abs(dit4),'k')
hold on
title('56nm Al2O3/SiC Dits vs Vg')
xlabel('Gate Voltage(V)')
ylabel('Dits Cm^-2/ev')
legend('1Khz','1Mhz','10Khz','100Khz')
References


24) [Online]. Available http://www.srim.org/