Study of Semiconductor Near-Surface Region using Photoconductive Decay Technique

A Thesis in
Electrical Engineering
by
Divij Bhatia

© 2011 Divij Bhatia

Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Science

December 2011
The thesis of Divij Bhatia was reviewed and approved* by the following:

Jerzy Ruzyllo
Distinguished Professor of Electrical Engineering
Thesis Advisor

Suman Datta
Professor of Electrical Engineering

Kultegin Aydin
Head of the Department of Electrical Engineering

*Signatures are on file in the Graduate School
Abstract

The photoconductive decay (PCD) technique is a commonly used to study bulk characteristics of semiconductor materials. This work takes forward the idea of using solid state laser technology for studying the near-surface region of a semiconductor or the interface region of a semiconductor - dielectric interface. The choice of laser (wavelength) is material dependent and the tool, built around a probe station, has the ability to measure pre-patterned small geometry samples. A detailed description of the experimental procedure is provided. The tool has the ability to form reliable ohmic contact with dielectric of thickness less than 50nm without the need for any additional etching steps. The tool is then used to monitor silicon surface change after an HF clean following which it is left to stand in the ambient over time. The results are compared with a surface sensitive contact angle tool. The near-surface PCD (ns-PCD) technique is compared to conventional microwave PCD commonly used to measure bulk lifetime of a semiconductor. The near-surface tool shows a shorter lifetime value for the back surface than the polished front surface of the sample, while microwave PCD gives the same lifetime value for both surfaces. Thus the surface sensitivity of the tool is established. Next thin dielectrics grown on semiconductors are explored using the ns-PCD technique. The time limitation for the diffusion/oxidation furnace to form high quality silicon oxide on silicon is determined to be 8 minutes. This is
shown by observing the PCD lifetime that reflects the interface quality of the oxide-silicon. Two different dielectrics in alumina and tantalum oxide are grown on silicon and the PCD plots are compared. The importance of laser choice is demonstrated by taking measurements using 658nm and 980nm lasers. The former shows a more defective interface in the case of tantalum oxide. A different semiconductor material in gallium antimonide is considered in another experiment. One sample is degreased using acetone and IPA clean while the other sample is cleaned using HCl. Alumina is grown on both samples using atomic layer deposition. ns-PCD shows that HCl degrades the surface of GaSb. However forming gas anneal shows an improvement in near surface lifetime implying that HCl clean is needed to remove the uncontrolled GaO and SbO formed under ambient. Lastly it is shown that ns-PCD can be used to explore three dimensional fin structures. An ungated InGaAs quantum well fin structure is grown for this purpose. Nine devices with decreasing fin width are measured using ns-PCD. The quality of the grown fins is reflected in the plots obtained.
# Table of Contents

List of Figures .......................... viii

List of Tables .......................... xi

Acknowledgements ......................... xii

1 Introduction ............................ 1

   1.1 Motivation ........................... 1

   1.2 Thesis Outline ....................... 2

2 Background ............................. 4

   2.1 Time Constants ....................... 4

   2.2 Photo-Generation of Charge Carriers .... 5

   2.3 Charge Carrier Recombination ........... 8

   2.4 Surface and Interface Recombination .... 9

   2.5 Photo-Conductive Decay Measurement ... 12

3 Scope and Objectives ..................... 14
# Experimental Procedure 16

## 4.1 Lifetime Measurement Using Near-Surface PCD 16

- **4.1.1 Experimental Setup** 16
- **4.1.2 Measurement Procedure** 18
- **4.1.3 Charge Carrier Lifetime Determination** 20

## 4.2 Temporary Contact Formation 21

## 4.3 Contact Angle Measurement 24

## 4.4 Sample Preparation 25

- **4.4.1 Surface Sensitivity Measurements** 25
- **4.4.2 Semiconductor - Dielectric Interface study** 26
- **4.4.3 Measurements of Fin Structures** 28

# Results and Discussions 30

## 5.1 Monitoring Silicon Surface Change on Exposure to Ambient Air 30

## 5.2 Lifetime Comparison using ns-PCD and μ-wave PCD 33

## 5.3 Oxygen Passivation of Silicon 34

## 5.4 Study of Al₂O₃ and Ta₂O₅ Grown on Silicon 36

## 5.5 GaSb/Al₂O₃ Surface Clean and Anneal Study 38

## 5.6 PCD Measurements of InGaAs QW Fins 39

# Summary and Conclusion 41

## Appendix A

- **Code Used to Determine Charge Carrier Lifetime** 46

vi
Appendix B

Original Near-Surface PCD Experimental Setup 47

Appendix C

Penetration Depth of Lasers in Materials 48

References 49
List of Figures

2.1 (a) Absorption coefficient for Si, Ge, and selected III-V compound semiconductor materials in the visible and near-infrared spectral region.[8] (b) Absorption coefficient for gallium antimonide (GaSb).[9] (c) Absorption coefficient for \( \text{In}_{1-x}\text{Ga}_x\text{As}. \)[9] .............................. 7

2.2 (a) Light induced carrier generation, (b) Electron trapping and de-trapping, (c) Electron re-trapping, (d) Hole trapping and de-trapping, (e) Hole recombination, (f) Electron recombination, (g) Auger recombination .................................................. 9

2.3 Energy bandgap chart for dielectrics and semiconductors used in the work described in the thesis. The dielectric constants for the materials are: \( \varepsilon_{\text{SiO}_2} = 3.9; \varepsilon_{\text{Al}_2\text{O}_3} = 9; \varepsilon_{\text{Ta}_2\text{O}_5} = 22; \varepsilon_{\text{HfO}_2} = 25 \)[13] .......................... 11

2.4 (a) PCD measurement experimental setup. (b) Photo-conductive decay curve and lifetime measurement. The lifetime is measured at \( 1/e \) of the peak value.[16] ......................................................... 13

4.1 Near-surface PCD tool block diagram ................................. 17
4.2 The photocurrent reaches a saturation value when the duration of illumination \( t_{ill} \) is greater than the rise time as in (a), otherwise it starts to decay before attaining steady state value as in (b).[2] 19

4.3 Nature of laser pulse. Pulse period in the figure is in \textit{nanoseconds}. 19

4.4 Plot of decreasing resistance \((+y-axis)\) vs. time \((\log_{10})\) after light is turned off in a photoconductance measurement of a p-type silicon rod.[14] 20

4.5 Lifetime Calculation 21

4.6 ns-PCD measurement for dielectric thickness less than 50\textit{nm} can be reliably performed using ns-PCD without the need for etching holes into the dielectric for contact. 22

4.7 Graphs depicting oxide breakdown and ohmic contact formation: (a,b) 10\textit{nm} silicon dioxide on p-type silicon (c,d) 5\textit{nm} alumina on p-type gallium antimonide. 23

4.8 TANTEC CAM WAFER II Contact-angle measurement tool 24

4.9 Three dimension fin structure with In\textsubscript{0.7}Ga\textsubscript{0.3}As as channel layer. High-k dielectric used was 4.5\textit{nm} \((1nm \ Al_2O_3 / 3.5nm \ HfO_2)\).[21] 29

4.10 Fin structures measurement using ns-PCD experimental setup. 29

5.1 Progression of water drop on silicon surface over time: (a) measured after etch (b) measured 7 \textit{hours} after etch. 31

5.2 Progression of photoconductance decay plots over time (indicated by arrow). 32
5.3 Comparison chart showing that both Contact angle and ns-PCD techniques used for studying silicon surface degradation over time, show the same trend. Time is in hours.

5.4 Photoconductive decay curve obtained by the ns-PCD tool for polished and unpolished surfaces of n-type prime Si wafer.[22]

5.5 Graph comparing \( \mu \) – wave PCD lifetime data with near-surface PCD lifetime data for front-side and back-side of silicon wafer.

5.6 Photoconductance curves for studying four samples with different duration of thermal oxidation time.

5.7 PCD curves for alumina and tantalum oxide grown on silicon for laser of wavelength: (a) 658nm (b) 980nm

5.8 Minority carrier lifetime for GaSb subjected to three different surface treatments.

5.9 PCD plots obtained for four of nine InGaAs fin structures.

6.1 Original near-surface PCD experimental setup [1]
List of Tables

4.1 Number of fins and fin width fabricated for In$_{0.7}$Ga$_{0.3}$As fin structure. 28

6.1 Penetration depth in Si, GaSb and InGaAs for lasers 658nm and 980nm 48
Acknowledgements

This work would not have been possible without support from several individuals. Firstly it was the enthusiasm of Dr. Jerzy Ruzyllo that made the development of the near surface PCD tool possible. Early development of the tool was done by Dr. Patrick Drummond as a part of his PhD studies. I would like to thank him for answering my questions about the tool right from the early stages of my work. Aditya Kshirsagar, PhD student under Dr. Ruzyllo and fellow labmate, who helped fabricate silicon - silicon oxide samples and also for his valuable inputs. Brittany Hedrick, for her help with microwave PCD measurments. Dr. Suman Datta, for agreeing to be on my committee. The following PhD students under Dr. Datta: Euichul Hwang, who fabricated samples with alumina and tantalum oxide on silicon and gallium antimonide; Lu Liu, for fabricating the InGaAs fin structure; Ashish Agrawal, for valuable discussions. Lastly, I would like to thank my parents for their trust and financial support.
Chapter 1

Introduction

1.1 Motivation

Semiconducting materials; semiconductors; are the driving force behind every electronic and opto-electronic technology of this day. They form the core materials of a multi-billion dollar industry that have formed the basis for human progress over the last half a century. Semiconductors are formed out of group IV, III-V and II-VI materials in the periodic table. Staying in accordance with the Moore’s Law, we are now at a stage where devices made out of semiconductors need high precision growth of $1nm - 1\mu m$ thick layers. It has become extremely crucial to examine interface perfection of grown material layers as well as the effect of abrupt termination of material lattice at the surfaces. It has thus become necessary to modify older techniques; using current technology; and develop measurement techniques that would provide better information specifically about surface properties rather than bulk properties. It is also important to note that the characterization technique needs to be applied to production and should not lower production efficiency.
A temporary contact near-surface photoconductive decay (ns-PCD) measurement technique was thus developed for this purpose. The ground-work for the tool was established by Patrick Drummond as described in [1]. His work included using the tool to study of pristine as well as samples with inherent imperfections (poly-crystalline and multi-crystalline silicon). This lab-built versatile tool can be easily fixed and modified based on the semiconductor material sample under question as described in this work. Provisions have been made to ensure that an idea about the surface condition and dielectric - semiconductor interface can be obtained without the need for any ‘extra’ processes on the sample in question as many other characterization techniques are known to require.

Applications of the tool is in front-end of the line for device manufacturing. This tool gives us an idea about the surface condition before dielectric deposition. It can give an idea about the quality of grown dielectric after deposition and before contact deposition. Thus manufacturing process related decisions can be made by using results obtained from this tool. This can lead to saving of time and crucial material and monetary resources. Also gate leakage due to thin oxide or bad oxide growth or highly rough surface that might prevent a capacitance - voltage measurement does not effect the ns-PCD technique.

1.2 Thesis Outline

In this work various passivation materials and cleaning methods have been explored using this tool and the viability of the tool to measure interface condition for semiconductors beyond silicon has been established. Chapter 2 covers the theoretical background required to understand photo-generation of charge carriers in a material
and various recombination mechanisms that can occur in the system under question. An idea about how photo-conductive decay measurements have been used historically is given. The scope and objectives are described in Chapter 3. A description and working procedure of the tool is then provided in Chapter 4. This chapter also covers a description of the samples used for this work. Chapter 5 explains the experiments conducted and conclusions obtained and forms the heart of this thesis. A summary and an idea of possible future work is offered as a conclusion.
Chapter 2

Background

Historically, the first photo-conductivity effect was recorded in 1873 by W. Smith, who observed that the resistivity of selenium was decreased by radiation shining on it. In 1905, Einstein explained the photoelectric effect. This opened a way to interpret the interaction of radiation with matter.[2] In 1950, Haynes and Shockley analysed the mobility and life of carriers in Germanium. They also studied how the lifetime of carriers would be shorter at the surface than in the bulk of a semiconductor.[3] In 1952, Shockley and Read laid down the foundations for recombination study in semiconductors.[4] In 1954, Stevenson and Keyes performed and first showed an extensive analysis of a photo-conductive based measurement [5] (a form of which is used in this work). In 1962 Robert Hall demonstrated the first solid state laser.[6]

2.1 Time Constants

The free lifetime of a charge carrier can be described as the time spent by the carrier in the conduction and valence band when it contributes to conduction. The minority
carrier lifetime is the free lifetime of minority carriers in the semiconductor. It is dependant on the presence of traps and recombination centers in the semiconductor and its value can be estimated from the Shockley-Read-Hall theory as described in section 2.3. In photo-conductive decay measurements the lifetime of minority carriers is obtained from the decay curve after a light source has been cut-off as described in section 2.5. The response time is described as the time required for the photo-current to reach 63% of its maximum value in the rise curve or 37% of its maximum value in the decay curve. In the presence of defect states the value of response time does not match the theoretical value. Rise time is described as the time required for photo-current to increase from 10% to 90% of maximum value in the rise curve. Similarly fall time is the time required for photo-current to decrease from 90% to 10% of maximum value in the decay curve. More on the theory of photo-current is given in section 2.5. The transit time is defined as the time required for charge carriers to reach the electrode after they are generated in the semiconductor.[2] Carrier capture time and emission time related to trapping and de-trapping is covered in section 2.3.

2.2 Photo-Generation of Charge Carriers

In a direct bandgap semiconductor charge carrier generation is instigated when the illumination photon energy ($h\nu$) is greater than the bandgap energy ($E_g$) of the material. The excess energy is dissipated as heat. In indirect bandgap semiconductors a part of the photon energy is given to phonons to initiate transitions to the bottom of the conduction band. Transitions may also occur at lower incident energies in the presence of impurity states within the bandgap of the material (figure 2.2).

The number of photons absorbed by the semiconductor is proportional to the intensity
of the incident photon flux $\Phi_0$. This flux decreases exponentially as its distance, $x$, increases from the surface of the material. The relation is given by Lambert’s law:

$$\Phi(x) = \Phi_0 [1 - R(\lambda)] e^{-\alpha x} \quad (2.1)$$

Here $R(\lambda)$ is the reflectivity at wavelength $\lambda$ and $\alpha$ is the absorption coefficient of the material. The latter is a function of the incident photon energy $h\nu$. Most of this energy is absorbed by a distance, $x = 1/\alpha$, in the material (since by equation 2.1, $\phi\left(\frac{1}{\alpha}\right) = \frac{\Phi_0}{e}$ under no reflection condition). [2, 7]

Figure 2.1 shows the absorption coefficient vs illumination energy for some semiconductors. The absorption edge begins approximately at the wavelength ($\lambda$) corresponding to energy $E_g$ (eV) of the semiconductor.

$$\lambda = \frac{hc}{E_g} = \frac{1.24}{E_g} \mu m \quad (2.2)$$

Since the photon flux is $\phi = \frac{\text{#photons}}{\text{sec.cm}^2}$; the total steady-state carrier generation rate per unit volume due to the incident light is given by:

$$G = \eta \phi \alpha \quad (2.3)$$

where $\eta$ is the quantum efficiency (defined as the number of electron-hole pairs generated for each incident photon). In terms of incident power density $P_{opt}$ (eV/sec.cm$^2$); this generation rate can be given as:

$$G = \eta \left(\frac{P_{opt}}{h\nu}\right) \alpha \simeq \eta P_{opt} \frac{\lambda(\mu m)}{1.24} \alpha \quad (2.4)$$

from equation 2.2.

The number of carriers generated is then obtained by $G.\tau$ product where $\tau$ (lifetime) depends on the number of defect states in the forbidden gap of the material.
Figure 2.1: (a) Absorption coefficient for Si, Ge, and selected III-V compound semiconductor materials in the visible and near-infrared spectral region.[8] (b) Absorption coefficient for gallium antimonide (GaSb).[9] (c) Absorption coefficient for In$_{1-x}$Ga$_x$As.[9]


2.3 Charge Carrier Recombination

When electrons are excited into the conduction band from the valence band, both free-electron and free-hole densities are built up. The direct recombination of free electrons and free holes is normally a less likely process than their indirect recombination via defect states in the forbidden zone. The latter are usually more numerous and have higher capture cross-sections for free carriers. In fact their presence can be assumed throughout the forbidden zone. The presence of trap states results in an increase of response time of excess carriers; while the presence of recombination centers controls the lifetime of the carriers. In a technique called sensitization, addition of recombination centers can increase the lifetime of one sign carrier (contrary to intuition) while decreasing the lifetime of the other carrier. The effect of trap states and recombination centers on lifetime are well analysed in reference [10].

Generation and recombination processes in a semiconductor is summarized in figure 2.2. In an indirect semiconductor, Shockley-Read-Hall (SRH) is the dominant recombination mechanism where excess carriers either recombine with the opposite charge carriers or find a trap center. Radiative recombination (resulting in light emission) dominates in direct bandgap materials like GaAs, while Auger recombination requires a high density of carriers and therefore dominates under high doping and high injection condition.[11]

In this study, SRH type recombination is given emphasis due to our focus on surfaces and interfaces where defect states are plentiful. The essentials of the models are covered in references: [4, 7].

The carrier capture (recombination/trapping) lifetime is given by:

\[ \tau_c \approx \frac{1}{v_{th} A n_r} \]  

(2.5)
The carrier emission (de-trapping) time is given by:

\[ \tau_e \approx \frac{\exp((E_F - E_T)/kT)}{v_{th} A n_t} \]  

(2.6)

where \( v_{th} \) is the thermal velocity of the carrier, \( A \) is the area of cross-section of the defect state, \( n_r \) is the number of defect states/cm\(^3\), \( n_t \) is the number of trapped carriers/cm\(^3\), \( E_T \) is the energy level of the trap and \( E_F \) is the fermi level.

### 2.4 Surface and Interface Recombination

At the surface of any material, the three-dimensional periodicity is lost resulting in surface states located within the forbidden gap of the material. Any charge on these states will cause a varying electrostatic potential on passing from the surface to the
interior resulting in band bending at the surface. Any relaxation, reconstruction, structural imperfections and adsorbed impurities will also contribute to the band-bending. These surface states act as source or sink for electrons and change the chemical and electrical properties of the surface of the material.[12] Further chemical treatment is usually done to clean the surface or engineer a specific charge on the surface of the semiconductor prior to processing. Such chemical treatment in inaccurate proportions can damage the surface. Growth of dielectric (a crucial step in device manufacturing) leads to imperfections at the interface between the dielectric and the semiconductor. This is especially the case when the dielectric is chemically and structurally different from the substrate on which it is being grown.

The effect of surface treatment on carrier lifetime was shown in the experiment conducted by Haynes and Shockley in 1950 [3]. It was stated that recombination at the surface might be expressed in the dimensions of velocity (s = cm/sec), “as if the carriers were disappearing out of the surface.” If we take into consideration equation 2.5, \( p_r = \frac{\#rec-centers}{cm^2} \) at the surface, thus recombination rate would have dimensions of velocity.

The effective lifetime was expressed as:

\[
\frac{1}{\tau} = \frac{1}{\tau_{bulk}} + \frac{1}{\tau_{surface}} \tag{2.7}
\]

For a sample with \( \tau_{bulk} = 100\mu sec \); sandblasting the surface resulted in more recombination states (\( s = 10^4 cm/sec \)) yielded short surface lifetimes (\( \tau_{surface} = 3\mu sec \)) given by the equation:

\[
\frac{1}{\tau_{surface}} = D \left( \frac{\pi}{2} \right)^2 (B^{-2} + C^{-2}) \tag{2.8}
\]

and for surface treatments resulting in long surface lifetimes (\( \tau_{surface} = 60\mu sec \)),

\[
\frac{1}{\tau_{surface}} = \frac{s}{B} + \frac{s}{C} \tag{2.9}
\]
where \( s = 200 \text{cm/sec} \); \( 2B \) and \( 2C \) were the dimensions of the sample; \( D \) was the diffusion coefficient.

Since the above study several attempts have been made to separate the bulk lifetime and surface lifetime from photoconductivity curves. In this work and in [1], experimental apparatus and methods are used such that the surface characteristics of the sample material are emphasized in the photoconductivity curves. It has been taken forward to explore dielectric-semiconductor interfaces. This is based on the fact that the dielectric has a wide bandgap (figure 2.3); so the energy of photons will not be enough to generate carriers in the dielectric. The dielectric will essentially be transparent to the incoming light enabling the study of the interface region.

Figure 2.3: Energy bandgap chart for dielectrics and semiconductors used in the work described in the thesis. The dielectric constants for the materials are: \( \varepsilon_{\text{SiO}_2} = 3.9 \); \( \varepsilon_{\text{Al}_2\text{O}_3} = 9 \); \( \varepsilon_{\text{Ta}_2\text{O}_5} = 22 \); \( \varepsilon_{\text{HfO}_2} = 25 \) [13].
2.5 Photo-Conductive Decay Measurement

The photo-conductive decay (PCD) measurement technique was used by Hornbeck and Haynes where they analysed the decay curve to study recombination and trapping in silicon.[14] Traditionally, xenon flashtubes and chopped incandescent light sources were used, but the onset of laser and sophisticated electronics now provides the required photon density to study even higher resistivity samples much more conveniently with lesser error.[15]

Figure 2.4 shows the experimental setup for PCD measurements. The excess carrier behaviour and lifetime calculation is also shown. It is calculated that for maximum photocurrent, the value of the load resistor $R_L$ should equal the sample resistance. The sample resistance can be obtained by the dark current (under no illumination). Modifications to the setup can include using a wheatstone bridge circuit, with the sample being one of the arms of the wheatstone bridge. An amplifier can be used to boost weak signals.[2]

The excess carrier behaviour can be derived from rate equations. The rate equation is given by:

$$\frac{dp}{dt} = G - R = G - \frac{p}{\tau_r} \quad (2.10)$$  

Carrier generation is given by:

$$p(t) = \tau_r G \left(1 - e^{-\left(t/\tau_r\right)}\right) \quad (2.11)$$

Carrier decay is given by:

$$p(t) = \tau_r G e^{-\left(t/\tau_r\right)} \quad (2.12)$$

The conductance of sample changes as:

$$\sigma(t) = q \left(\mu_n + \mu_p\right) p(t) \quad (2.13)$$
The current follows the change in sample conductance. That is reflected in the voltage drop across the load resistor which is given to the oscilloscope. The PCD curve, however, usually does not follow the predicted exponential behaviour due to recombination and trapping. Modelling such a curve is typically done using a notation of the form $e^{-(t/\tau)^\gamma}$ in equations 2.11 and 2.12. It is also possible to model trap density as a function of energy as shown in [17]. No such modelling is done in this work.
Chapter 3

Scope and Objectives

The idea of photoconductive based lifetime measurements has been covered in the previous chapter 2. The near-surface PCD tool was put together by Patrick Drummond and is described in [1]. His work has been taken forward as described in this thesis.

The work described in this thesis can be divided into three different categories. The first category covers the modification of the already developed tool for measuring patterned device structures with extremely small geometry size. This involved rebuilding the tool around a probe station. The measurement user-interface was the same as described in [1]. An additional code was written in MATLAB for lifetime calculation.

The second category demonstrates the surface sensitivity of the tool. Two experiments were conducted for this purpose. Contact angle and PCD measurements were performed on a silicon sample cleaned and then left in the same ambient conditions. The surface change monitored by contact angle were reflected by the ns-PCD tool (section 5.1). The second experiment demonstrated the tools’ higher capability to measure surface characteristics than conventional microwave PCD technique (section
5.2). The third category explores semiconductor samples with grown dielectric. In this work, the dielectrics of the order of one to ten nanometers are considered. It has been shown that it is not essential for the dielectric to be etched for the probes to make ohmic contact with the semiconductor (section 4.2). In a first experiment, silicon with high quality silicon oxide grown is studied. The minimum time required for the diffusion furnace to grow good quality oxide is concluded from the results (section 5.3). Alumina and tantalum oxide are grown on silicon and the interface formed by the two oxides is compared using ns-PCD. Alumina is shown to form a better interface with silicon for the same clean and dielectric growth conditions (section 5.4). In the next experiment alumina is grown on gallium antimonide. Here gallium antimonide surface cleaning is explored. One sample is subjected to alcohol clean; a second sample is subjected to HCl clean. The second sample is then annealed. The photoconductance results obtained are compared (section 5.5). An application of the tool in measuring three dimensional fin structures is shown as a demonstration of possible future work. PCD outputs for InGaAs quantum well fins of decreasing thickness were obtained. The data obtained shows low lifetime values for imperfectly grown fins (section 5.6).

Thus the work in this thesis demonstrates the ability of the near-surface PCD tool to be viable for future device research. The tool is easy to setup and can also be used for FEOL (front end of the line) characterization in a manufacturing setting on pre-patterned structures.
Chapter 4

Experimental Procedure

4.1 Lifetime Measurement Using Near-Surface PCD

4.1.1 Experimental Setup

A figure of the original ns-PCD experimental setup is shown in figure 6.1 [1]. A block diagram of the modified tool set up by the author for this study is shown in figure 4.1. The tool is essentially built around a typical probe station. The probes can be positioned on the sample on various positions as desired. A laser of wavelength 658 nm is mounted directly above the probes and positioned such that the laser beam falls exactly in between the two probes using sensitivity knobs. The laser diode can be easily changed if needed. A pulse generator HP8131A is the supply to the laser. The applied voltage, pulse width and time period can be varied as required. The two probes are connected to a supply (Keithley 236 source measure unit) through a potentiometer (500 KΩ) as shown. As mentioned in section 2.5, the optimum value of the resistance of the potentiometer ($R_L$) is equal to the sample resistance. This vari-
ation in photoconductivity output can be observed on the oscilloscope and the best resistance value can be thus determined experimentally. An oscilloscope (HP54501A) connected across $R_L$ captures the rate of change in voltage due to excess carrier modulation within the sample. A plot of voltage vs time is obtained on the oscilloscope. The data is collected by a computer to oscilloscope interface enabling further analysis. The tool is controlled by a visualbasic program on the computer [1] which helps one specify supply voltage to the sample aswellas collect data. It also gives an idea about the lifetime strictly for the typical case specified next. Typical value of laser voltage used is $2.5V$, the time period used is $200\mu sec$ and pulse duration used is 10% of the time period. In this work a modified program written in MATLAB by the author (Appendix A) gives the user more freedom and enables lifetime measurement by varying the pulse duration/time period in the pulse generator and/or the time scale in the oscilloscope.

Figure 4.1: Near-surface PCD tool block diagram
4.1.2 Measurement Procedure

The first step is to ensure that the laser holder is in line with the microscope and the probes are clearly under the laser holder but about 2\text{mm} apart. The sample is placed on the chuck and brought below the probes and the probes are lowered on the sample. The laser is then placed into the holder making sure its tightly fit and vertical, making sure that the beam falls as little as possible on the two metal probes. The resistance of the potentiometer is predetermined but can be varied depending on the voltage drop across the resistor \textit{vs} voltage drop across the sample. The current output should be large enough but not too large. It is important that ohmic contact is formed between the semiconductor and the probes, especially when there is a dielectric layer present through which the probes have to penetrate. To check if the contact is ohmic, blocking or injecting; negative to positive periodically increasing voltage is passed and current value is observed (section 4.2).

The laser can now be switched on and the PCD output can be observed on the oscilloscope. Rotatory knobs can be used to position the laser for the best output. Potentiometer resistance can also be varied as required. The laser voltage, and pulse period can be changed. As shown in figure 4.2, the duration of the laser ON pulse has an effect on the number of excess charge carriers generated as well as carrier decay lifetime. It is important that enough charge carriers are generated for decay study, however increasing the pulse period to ensure maximum carrier generation is not necessary. In case of extremely short pulse period it is important to know that the laser on/off is not instantaneous as seen in figure 4.3.
Figure 4.2: The photocurrent reaches a saturation value when the duration of illumination ($t_{ill}$) is greater than the rise time as in (a), otherwise it starts to decay before attaining steady state value as in (b).[2]

Figure 4.3: Nature of laser pulse. Pulse period in the figure is in nanoseconds.

Once satisfactory output is obtained on the oscilloscope, data collection can be performed using the visualbasic user-interface. The data obtained can be plotted using any graphical software. Lifetime can be calculated manually or using the MATLAB code provided in Appendix A.
4.1.3 Charge Carrier Lifetime Determination

It was shown previously in figure 2.4, that lifetime is calculated from the decay curve at value $1/e$ of peak. Section 2.5 covered that the curve need not be exponential in nature due to trapping and re-trapping of charge carriers before recombination with the opposite charge carrier. Figure 4.4 demonstrates how instantaneous drop in current after light is turned off is mainly due to recombination of excess carriers with recombination centers/opposite charge carriers.

![Plot of decreasing resistance (+y-axis) vs. time (in log_{10}) after light is turned off in a photoconductance measurement of a p-type silicon rod.][14]

Figure 4.4: Plot of decreasing resistance ($+y$ - axis)) vs. time (in log_{10}) after light is turned off in a photoconductance measurement of a p-type silicon rod.[14]

In the near-surface PCD technique, in order to focus on interface and surface recombination (with recombination centers), lifetime is determined by calculating the slope at point $0.8 \times peak$. Then the corresponding time at $peak/e$ on the same slope is considered and termed as the near-surface lifetime ($\tau_{ns}$). Figure 4.5 offers a visual of this method for a typical PCD curve. The lifetimes measured in this work are almost all near-surface lifetimes.
4.2 Temporary Contact Formation

Ohmic contact formation of the semiconductor with the probes is essential for PCD measurements. The procedure to check for contact formed was previously covered in section 4.1.2. It is more difficult to form ohmic contact with deposited dielectric on the semiconductor. In this section the study conducted to form repeatable contact using the ns-PCD tool is described.

For dielectrics with thickness greater than $50\text{nm}$ sample processing (patterning and etch) is required prior to ns-PCD measurements. This additional step is however not required for samples with dielectric thickness less than $50\text{nm}$. The application of appropriate voltage breaks the dielectric and forms reliable ohmic contact. However care must be taken that the contact is not ‘lost’ during measurement. This observed occurrence is summarized in figure 4.6.

![Lifetime Calculation Method](image)

**Figure 4.5: Lifetime Calculation**

4.2 **Temporary Contact Formation**

Ohmic contact formation of the semiconductor with the probes is essential for PCD measurements. The procedure to check for contact formed was previously covered in section 4.1.2. It is more difficult to form ohmic contact with deposited dielectric on the semiconductor. In this section the study conducted to form repeatable contact using the ns-PCD tool is described.

For dielectrics with thickness greater than $50\text{nm}$ sample processing (patterning and etch) is required prior to ns-PCD measurements. This additional step is however not required for samples with dielectric thickness less than $50\text{nm}$. The application of appropriate voltage breaks the dielectric and forms reliable ohmic contact. However care must be taken that the contact is not ‘lost’ during measurement. This observed occurrence is summarized in figure 4.6.
Figure 4.6: ns-PCD measurement for dielectric thickness less than 50\(nm\) can be reliably performed using ns-PCD without the need for etching holes into the dielectric for contact.

The following two tests demonstrate contact formation using the ns-PCD tool as well as reliable ohmic behaviour once contact is formed. The experiments were carried out for a \(p\)-type silicon sample with a 10\(nm\) grown oxide (\(Sample\ 4\) in section 4.4.2) and a \(p\)-type gallium-antimonide sample with a 5\(nm\) grown aluminium-oxide using PEALD (plasma-enhanced atomic layer deposition) technique.

For the first test, once probes were lowered on the sample under question, input voltage was gradually increased and current value was noted. Figure 4.7 shows a region of no contact, contact formed and ohmic behaviour. Once the contact was formed, a sweep from negative to positive voltage was done and the resulting current was observed. Silicon showed fluctuations in current but gallium antimonide showed good ohmic behaviour. It was generally observed that highly doped samples showed constant current values while more intrinsic samples showed fluctuations in current. The
breakdown voltage in the graphs do not represent the dielectric breakdown voltage as the samples were in series with a load resistor.

Figure 4.7: Graphs depicting oxide breakdown and ohmic contact formation: (a,b) 10nm silicon dioxide on p-type silicon (c,d) 5nm alumina on p-type gallium antimonide.
4.3 Contact Angle Measurement

Contact angle measurements for surface analysis were done using a TANTEC CAM WAFER II commercial contact angle measuring system (figure 4.8).

Figure 4.8: TANTEC CAM WAFER II Contact-angle measurement tool

The system is interfaced through a video capture card to a computer where the contact angle is calculated using a software application. A sessile drop method is employed where a $20 - 30\mu L$ drop of deionized water is dropped on the surface of the sample using a $5mL$ syringe. The real-time image of the droplet can be seen on the computer. The base and height of the droplet is measured using appropriate markers (user-specified). The measured contact angle is calculated via "the half-angle method" by the software using:

$$\theta = 2 \times \arctan \left( \frac{h}{r} \right)$$

where $h$ is the height of the drop, $r$ is the radius (horizontal) and $\theta$ is the contact angle made by the drop with the surface of the sample.[18]
4.4 Sample Preparation

4.4.1 Surface Sensitivity Measurements

The surface sensitivity of the PCD tool was established by comparison with the TANTEC contact angle tool (section 4.3). Two pieces from a bare silicon wafer ($p - type$ prime $< 100 >$ silicon of resistivity value $38 - 63\Omega cm$; thickness of $650 - 700\mu m$) were dipped in hydrofluoric acid ($HF$) solution of a $1 : 50$ concentration for 2 minutes to remove the native oxide. The wafers were then rinsed with deionized water and blown dry with nitrogen. Contact angle and PCD lifetime measurement were carried out immediately after the etch and then periodically. Both samples were kept in the same ambient conditions. The volume of drop used for contact angle measurement was $20\mu L$. The laser voltage used for PCD measurement was $2.8V$ and the laser-on pulse width was $20\mu sec$. The laser position was determined before the experiment was started and was kept unchanged. A voltage of $7V$ was supplied to the circuit and the potentiometer was set to a resistance of $10K\Omega$ for the entirety of the experiment. Three values of lifetime and contact angles were taken at each measurement on randomly chosen areas of the samples and then an average value was considered. After about one week, the same samples were etched again and a the same procedure was repeated.

A second experiment involved comparing the ns-PCD tool with a conventional non-contact $\mu - wave$ PCD commonly used to measure the bulk lifetime of minority carriers in a material. The $\mu - wave$ PCD tool used for this study had a light emitting diode (LED) of wavelength $870 - 890nm$ and a laser-on pulse width of $150\mu s$ and a time period of $1ms$. A description of the tool can be found in [19]. The sample wafer used for this study was a $n - type$ prime $< 100 >$ silicon of resistivity $5\Omega cm$; thickness
of 400µm, treated with $HF : H_2O$ solution of 1 : 100 concentration for 30 seconds and then after DI water rise and nitrogen blow dry was treated to wet thermal oxidation at 1000°C to grow an oxide of thickness 50nm. No additional preparation was required for the purpose of characterization. The measurement was done on the unpolished back-side of the wafer and the polished front-side using both techniques.

### 4.4.2 Semiconductor - Dielectric Interface study

Charge carrier lifetime is directly related to imperfections in a material. If a layer of dielectric is grown on a semiconductor, it leads to greater number of defect states near the interface. Since most MOSFETs work such that the minority carriers flow from source to drain extremely close to this dielectric - semiconductor interface, finding the right dielectric for the semiconductor as well as developing cleaning techniques for the best interface is crucial. It was described in section 2.4, that the laser used for photoconductance study is essentially transparent to the dielectric. Thus using the same idea as before, it is possible to study the interface region using the ns-PCD technique.

To study the effect of oxide passivation, dry oxidation of four samples from the same wafer ($p$-type prime < 100 > silicon of resistivity 11–20Ωcm; thickness 700–775µm) for different amount of time in order to grow thin high quality silicon dioxide ($SiO_2$). The samples were dipped in $HF : H_2O$ solution of 1 : 50 concentration for five seconds to remove the native oxide. They were then rinsed with deionized water and blown dry with nitrogen. *Samples 1, 2, 3 and 4* were oxidized for two, eight, fifteen and sixty minutes respectively. Oxidation was carried out in a diffusion furnace at a temperature of 800°C. Due to limitations of the ellipsometer used, only the oxide thickness of *Sample 4* could be accurately determined and was measured to be 93.35Å.

26
Silicon with high-k dielectrics ($Al_2O_3, Ta_2O_5$), grown using atomic layer deposition (ALD) were measured using the ns-PCD tool. The substrate was $p-type$ prime $< 100 >$ silicon with a doping concentration of about $1E17cm^{-3}$. The cleaning sequence before dielectric deposition was the same for both samples. It involved ten minute acetone, ten minute isopropanol, fifteen minute SC1 and fifteen minute SC2 solution clean; all performed at room temperature. The ALD growth rate was 1.0Å/cycle for aluminum oxide ($Al_2O_3$) and 0.57Å/cycle for tantalum oxide ($Ta_2O_5$) at a temperature of $300^\circ C$. The dielectric thickness in both cases was 5nm. The samples were then annealed at $300^\circ C$ for sixty minutes. Photoconductance decay curves were obtained using two lasers of wavelengths 658nm and 980nm. The laser pulse was 10% ON of 200µsec total period. The supply voltage was 7Volts and the load resistance used was 35KΩ. The obtained output and lifetime values were compared.

Gallium antimonide ($GaSb$) is a semiconductor of a bandgap of 0.7eV offering high mobility for electrons and holes than silicon. The drawback of the material is that it readily forms inferior quality, uncontrolled gallium oxide and antimony oxide under ambient. Removing these native oxides using cleaning methods followed by high quality dielectric growth is still under extensive research. In this study photoconductance decay output for tellurium doped ($n-type$) $< 100 >$ substrates with 5nm thick aluminum oxide grown using ALD process (similar to previous experiment) was measured. Three samples with different growth methods were considered. Sample $S51$ was the control sample, it was subjected to 5 minute acetone and isopropanol clean at room temperature. Sample $S52$ was further subjected to a 10 minute $HCl : H_2O$ (concentration 1 : 2) clean and IPA rinse. Sample $S10$, besides an $HCl$ clean, was subjected to forming gas anneal (FGA) for 30 minutes at $350^\circ C$. The supply volt-
The age for photoconductance measurements was $1 - 2 \text{Volts}$. The load resistor used was $30 \text{M}\Omega$. The laser used was of $980 \text{nm}$ wavelength. Laser supply voltage was $1.9 \text{Volts}$. The ON period was $10\%$ of $100 \mu\text{sec}$ total period.

### 4.4.3 Measurements of Fin Structures

Three dimensional FinFET devices have been declared as the future of transistor technology by Intel [20]. These devices offer more gate control, while reducing short-channel effects and surface scattering of carriers. Photoconductance measurements of $\text{In}_{0.7}\text{Ga}_{0.3}\text{As}$ quantum well structure shown in figure 4.9. The fabrication details are covered in [21]. In this sample the high-k dielectric used was $1nm\text{Al}_2\text{O}_3/3.5nm\text{HfO}_2$. The source and drain contact was deposited on the dielectric. No gate metal was deposited. A total of nine such devices with decreasing fin width but increasing number of fins were fabricated in a row (Table 4.1). Laser light from a $658\text{nm}$ laser was shone in between source and drain contacts as depicted in figure 4.10. Probes were mounted on the source and drain each. The laser pulse was $10\%$ ON of $200 \mu\text{sec}$. A load resistor ($R_L$) of $23K\Omega$ was used. Current in micro-amperes was observed beyond $3V$. PCD measurements were taken at $5\text{V}$ supply voltage.

<table>
<thead>
<tr>
<th>Fin Width</th>
<th>C1</th>
<th>C2</th>
<th>C5</th>
<th>C7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planar</td>
<td>1000nm</td>
<td>300nm</td>
<td>100nm</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1: Number of fins and fin width fabricated for $\text{In}_{0.7}\text{Ga}_{0.3}\text{As}$ fin structure.
Figure 4.9: Three dimension fin structure with In$_{0.7}$Ga$_{0.3}$As as channel layer. High-k dielectric used was 4.5$nm$ ($1nm$ Al$_2$O$_3$ / $3.5nm$ HfO$_2$).[21]

Figure 4.10: Fin structures measurement using ns-PCD experimental setup.
Chapter 5

Results and Discussions

This chapter covers the analysis and results obtained from the experiments described in Chapter 4. Each section describes one experiment unlike the previous chapter where the experimental methods were grouped.

5.1 Monitoring Silicon Surface Change on Exposure to Ambient Air

The aim of this experiment was to demonstrate the surface sensitivity of the near surface PCD tool. This was achieved by comparing it with the surface-sensitive contact angle measurement tool (section 4.3). The experimental method has been described in section 4.4.1. The three figures below explain the results.

Figure 5.1 shows that the contact angle of the water drop reduces as native oxide grows on the silicon surface. This is because silicon is hydrophobic while silicon dioxide is hydrophilic. The silicon surface after etch is hydrophobic and it makes a transition to a somewhat hydrophilic surface due to native oxide formation. This
change takes place over 15\textit{hours} time span. The angle values range from a maximum of 65° for silicon to 40° for oxidized surface (figure 5.3).

Figure 5.2 shows that the generated excess carriers decay more quickly, the more the silicon surface is exposed to the ambient air. After HF etch, the surface of the silicon sample is hydrogen passivated and has a positive charge. The carriers generated by the laser in the $p$ – $type$ sample will be more attracted to the surface. But the surface is relatively clean at this point resulting in a relatively longer minority carrier lifetime. As time passes the positive charge on the surface is neutralised and native oxide begins to form on the silicon surface. The laser beam might break some of these bonds as they are weak, resulting in a surface of imperfections and dangling bonds. These act as recombination centers for excess minority carriers and the lifetime is reduced. The lifetime values range from 30$\mu$sec for bare surface to 8$\mu$sec for surface with native oxide (figure 5.3).

A comparative graph of measured contact angle and lifetime versus the time that the samples are exposed to the ambient is shown in figure 5.3. The two peaks are due to surface clean using HF. Within a period of about 15\textit{hours} there is a sharp change in the surface characteristics. The graph shows that ns-PCD technique follows the contact angle tool in detecting surface chemical change.

![Figure 5.1: Progression of water drop on silicon surface over time: (a) measured after etch (b) measured 7 hours after etch.](image)
Figure 5.2: Progression of photoconductance decay plots over time (indicated by arrow).

Figure 5.3: Comparison chart showing that both Contact angle and ns-PCD techniques used for studying silicon surface degradation over time, show the same trend. Time is in hours.
5.2 Lifetime Comparison using ns-PCD and $\mu$-wave PCD

This experiment was initially conducted to demonstrate the importance of surface polishing. Near surface PCD measurements of the polished front and unpolished back surface of the same wafer yielded the results shown in figure 5.4. The same wafer was then subjected to microwave PCD measurement to compare the two methods. The details of the wafer used and the method are found in section 4.4.1.

![Photoconductive decay curve obtained by the ns-PCD tool for polished and unpolished surfaces of n-type prime Si wafer.][22]

As can be seen in figure 5.5, the measured charge carrier lifetime is heavily bulk dominated and is around 100$\mu$s. $\mu$ - wave PCD gives the same lifetime value for both polished and unpolished side of the sample. On the other hand the near-surface PCD tool gives a lower lifetime value ($\tau_{ns} = 23.55\mu$s) for the polished side and even lower ($\tau_{ns} = 7.15\mu$s) for the rear and unpolished side of the wafer. The bulk lifetimes
obtained ns-PCD tool again show the order of 100\(\mu\)sec, \textit{i.e.} same as \(\mu-wave\) PCD tool. The back side does not show bulk diffusion as majority of the excess minority carriers recombine at the surface. Thus the ns-PCD tool is clearly more sensitive to surface measurements, than the \(\mu-wave\) PCD tool.

![Graph comparing \(\mu-wave\) PCD lifetime data with near-surface PCD lifetime data for front-side and back-side of silicon wafer.](image)

**Figure 5.5:** Graph comparing \(\mu-wave\) PCD lifetime data with near-surface PCD lifetime data for front-side and back-side of silicon wafer.

### 5.3 Oxygen Passivation of Silicon

The near-surface PCD tool has applications in studying the dielectric semiconductor interface region as discussed earlier (section 2.4). In order to establish this, silicon/silicon-oxide samples with varying thickness of high-quality oxide were used (maximum thickness was 9.3\(nm\)). The details of the sample and oxide growth is covered in section 4.4.2. The photoconductance decay curves measured are shown in figure 5.6.
Figure 5.6: Photoconductance curves for studying four samples with different duration of thermal oxidation time.

It is evident that Sample 1 has a defective interface since most of the generated excess minority carriers recombine and are lost at the surface. The lifetime values obtained are 11 µsec for Sample 1 and 20 µsec and over for the rest. There are also not enough carriers available to show significant diffusive bulk behaviour like the other three samples due to the higher carrier recombination. Oxygen passivation fulfils dangling bonds and the interface condition is improved by greater passivation. Thus lesser carriers are lost due to recombination at the interface. As the oxide thickness increases the surface lifetime is seen to increase and more carriers diffuse into the bulk. This demonstrates a limitation of the diffusion/oxidation furnace for fabricating good quality oxides under 8 minutes.
5.4 Study of Al\textsubscript{2}O\textsubscript{3} and Ta\textsubscript{2}O\textsubscript{5} Grown on Silicon

The dielectric/semiconductor interface measurement study using ns-PCD is taken further in this experiment. Also the importance of choice of laser for near surface measurements is demonstrated. 5\(\text{nm}\) of high - k dielectrics, alumina (Al\textsubscript{2}O\textsubscript{3}) and tantalum oxide (Ta\textsubscript{2}O\textsubscript{5}) are grown on two different samples from the same silicon substrate. The energy band bandgap comparison for alumina, tantalum-oxide and silicon is given in figure 2.3. The details of the sample and experimental method is covered in section 4.4.2.

The photoconductance decay curves obtained using lasers of two different wavelengths are compared in figure 5.7. In this study the natural logarithm of the decay data is plotted versus time. Thus an exponential decay will show as a linear decay under natural log condition. This is observed for most of the part in the figure below. The 980\(\text{nm}\) laser gives a higher lifetime value than 680\(\text{nm}\) laser due to its greater penetration depth (Appendix C) implying more bulk characteristics. It shows exponential decay for both samples and the near-surface lifetime values are nearly equal (\(\tau = 17\mu\text{sec}\)). The 658\(\text{nm}\) laser measurements display a quick decay (fast recombination) for the Ta\textsubscript{2}O\textsubscript{5} sample followed by an exponential behaviour. This behaviour was repeatable which indicates a more defective interface for Ta\textsubscript{2}O\textsubscript{5}/Si. It therefore shows a lower near-surface lifetime (12\(\mu\text{sec}\)) than the Al\textsubscript{2}O\textsubscript{3} sample (15\(\mu\text{sec}\)). Thus the 658\(\text{nm}\) laser shows more useful near-surface characteristics than the higher wavelength 980\(\text{nm}\) laser.
Figure 5.7: PCD curves for alumina and tantalum oxide grown on silicon for laser of wavelength: (a) 658nm (b) 980nm
5.5 GaSb/Al₂O₃ Surface Clean and Anneal Study

The final step for interface analysis involved study of III-V semiconductors with high-
k dielectric. A GaSb/Al₂O₃ structure was chosen for this purpose. Three samples were considered: S51 - Degreased; S52 - Degrease + HCl; and S10 - Degrease + HCl + FGA with processes described in detail in section 4.4.2. The penetration depth for GaSb with 980nm laser is 250nm (Appendix C) which indicates that the excess carriers generated are very close to the interface. Thus there would be heavy loss of carriers due to interface recombination. This fact and a possible heavy doping made it difficult to obtain photoconductance decay curves for the samples.

![PCD plots for GaSb/Al₂O₃ Surface Clean and Anneal](image)

Figure 5.8: Minority carrier lifetime for GaSb subjected to three different surface treatments.
In figure 5.8 it is observed that between the time $25\mu sec$ and $30\mu sec$, all three curves display a sharp drop and rise in excess charge carriers. This can be explained by referring to figure 4.3. It can be seen that after laser OFF, for a period of $50nsec$ the laser pulse shows a short rise and fall. This is enough energy for excess carriers to be generated for $GaSb$ due to its short bandgap of $0.7eV$.

The natural logarithm of PCD curves is plotted versus time. In all three curves there is fast recombination observed followed by exponential behaviour. The near-surface lifetimes represent the fast recombination. As can be seen from the figure, the lifetime values are of the order of hundreds of nanoseconds. $HCl$ treatment in $S52$ makes the wafer surface rougher than simple degrease as in $S51$ [23], resulting in a shorter interface lifetime value. Forming gas anneal ($S10$) improves the interface condition. Further study of the same samples can be found in [23].

### 5.6 PCD Measurements of InGaAs QW Fins

This experiment studies the quality of fin fabrication using ns-PCD, of nine devices with gradually reducing fin width. The details of the quantum well fin structure and measurement procedure can be found in section 4.4.3. This is also the first quantum well device measured using this tool. The penetration depth for $658nm$ laser in InGaAs is calculated in Appendix C.

The current values (laser OFF) measured from C1 through C9 (table 4.1) at $5V$ supply, shows a drop from $7\mu A$ for samples C1 to C5 to less than $1\mu A$ for samples C6 to C9. The photoconductance lifetime obtained (figure 5.9) points to degradation of fin quality from C7 to C9 as the lifetime drops from $11\mu sec$ to $5\mu sec$. C1 represents planar structure behaviour. C2 and C5 show near-surface lifetime comparable to C1.
indicating good quality fin growth.

Figure 5.9: PCD plots obtained for four of nine InGaAs fin structures.
Chapter 6

Summary and Conclusion

The ability of the near-surface photoconductive decay tool to characterize semiconductor-dielectric interface region has been demonstrated in this work. The technique uses the portability of solid state lasers which is a relatively new technology. The tool is easy to set up and requires very little capital investment. It has a potential in being a front-end of the line testing tool in a manufacturing setting.

The requisite theoretical and historical background has been covered in this thesis. That is followed by the experimental method that must be followed to acquire consistent results. It is shown that the technique is sensitive to the near-surface region by appropriate choice of lasers. The technique follows the contact-angle tool in measuring surface chemical change of silicon due to native oxide growth. It shows greater sensitivity to surface condition when compared to microwave PCD technique. Thin SiO$_2$ grown on silicon shows larger near-surface lifetime as the oxide thickness is increased, that is, as the oxygen passivation of the surface is increased. This result is used to conclude the minimum time needed for high quality oxide to be grown in the thermal diffusion furnace. This is an important consideration that might help save
valuable monetary and material resources in a manufacturing setting. Different decay characteristics shown by $\text{Al}_2\text{O}_3$ and $\text{Ta}_2\text{O}_5$ grown on silicon are studied. It is concluded that $\text{Al}_2\text{O}_3$ formed a better interface with silicon than $\text{Ta}_2\text{O}_5$. The importance of choosing a laser that highlights the near-surface region is demonstrated. Gallium antimonide samples with $\text{Al}_2\text{O}_3$ were subjected to different clean and FGA anneal and the result on photoconductance lifetime was observed. The surface roughness was increased due to $\text{HCl}$ clean. The interface condition showed improvement with anneal. This was reflected in the near-surface lifetimes obtained. Lastly, ungated InGaAs quantum well fin structures were built and characterized to demonstrate that the technique can be used to study fin growth quality.

Future work using the tool might include modelling and fitting of the decay curves obtained. Appropriate cleaning and dielectric deposition of Fin structures is an exciting area where the near-surface PCD tool can be very useful. Other semiconductors like gallium nitride growth on sapphire for example will require investment in a ultraviolet laser of higher energy. An oscilloscope of $GHz$ frequency will make the tool more sensitive. Thus, there is scope for making the tool better. Also the tool will find use in a wide range of applications for semiconductor material study.
Appendix A

Code Used to Determine Charge Carrier Lifetime:

The following code collects data from the .txt file generated when the data collection command is given. The data is in terms of 'data points', which is converted to millivolts by subtracting the start value and then multiplying with the incrementing value of voltage. The program generates the PCD plot vs time. It then asks the user for the peak and 0.8*peak datapoints for slope calculation. Then using the equation $y = mx + c$; where $m$ is the calculated slope, $c$ is peak point (y-intercept) and $y$ is taken to be $1/e$ of the peak; the corresponding value of $x$ is determined. This gives the minority carrier lifetime. The output plot is then provided with $\log_{10}(PCD_{output-mV})$ or $\log_e(PCD_{output-mV})$ on the y-axis vs time on the x-axis along with the calculated lifetime.

MATLAB code to find lifetime from obtained data:

```matlab
[diff,t]=time();
t2=0:diff:t;
importfile('file-address');
a0=data;
[a0_V]=run_first(t2,a0);
```

43
[a2]=data_processing(t2,a0_V);

[slope1,y_intercept]=manual_slope();

l1=lifetime(slope1,y_intercept);

graf_it(t2,a2,l1);

**MATLAB function for generating time vector:**

function [diff,t]=time()

diff=input('time_diff =','s');

diff=str2double(diff);

t=0+(498*diff);

**MATLAB function for converting data points to Volts:**

function [data_V]=run_first(time,data)

%multiplies amplitude increment

amp_inc=input('ampitude increment=','s'); amp_inc=str2double(amp_inc);

data_V=amp_inc*data;

figure; plot(time,data_V)

title('after amp_inc')

**MATLAB function for subtracting offset:**

function [data1]=data_processing(time,data)

min=input('minimum value=','s'); min=str2double(min);

data1=data-min;
MATLAB function to calculate slope:

```matlab
function [slope,y1]=manual_slope()
x1=input('peak point: x1=','s'); x1=str2double(x1);
y1=input('peak point y1=','s'); y1=str2double(y1);
next_point_ref_surface=0.8*y1
next_point_ref_bulk=y1/exp(1)
x2=input('x2=','s'); x2=str2double(x2);
y2=input('y2=','s'); y2=str2double(y2);
slope=(y2-y1)/(x2-x1);
```

MATLAB function to calculate lifetime:

```matlab
function [lifetime]=lifetime(slope,peak)
lifetime=peak*(-0.632)/slope
```

MATLAB function to display PCD output graph:

```matlab
function []=graf_it(time,data1,life1)
figure;plot(time*1E6,log(data1*1E3),'LineWidth',3)
xlabel('time (\musec)','FontSize',14,'FontWeight','b');
ylabel('log_e[PCD output (milli-volts)]','FontSize',14,'FontWeight','b');
title('title-name','FontSize',14,'FontWeight','b');
legend('name');
```
MATLAB function for file import:

function importfile(fileToRead1)  %IMPORTFILE(FILETOREAD1)

    % Imports data from the specified file
    
    % FILETOREAD1: file to read
    
    DELIMITER = ' '; HEADERLINES = 5;
    
    % Import the file
    
    newData1 = importdata(fileToRead1, DELIMITER, HEADERLINES);
    
    % Create new variables in the base workspace from those fields.
    
    vars = fieldnames(newData1);
    
    for i = 1:length(vars)
        
        assignin('base', vars{i}, newData1.(vars{i}));
        
    end
Appendix B

Original Near-Surface PCD Experimental Setup:

Figure 6.1: Original near-surface PCD experimental setup [1]
Appendix C

The penetration depth of lasers $658\text{nm}$ ($1.88\text{eV}$) and $980\text{nm}$ ($1.27\text{eV}$) for Silicon, GaSb and InGaAs are covered in the table below ($\alpha$ is obtained from figure 2.1):

<table>
<thead>
<tr>
<th>$E_g$ (eV)</th>
<th>658nm laser</th>
<th>980nm laser</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\alpha$ ($\text{cm}^{-1}$)</td>
<td>penetration depth</td>
</tr>
<tr>
<td><strong>Silicon</strong></td>
<td>1.12</td>
<td>$2.5 \times 10^3$</td>
</tr>
<tr>
<td><strong>GaSb</strong></td>
<td>0.7</td>
<td>$4 \times 10^5$</td>
</tr>
<tr>
<td><strong>InGaAs</strong></td>
<td>0.6</td>
<td>$1 \times 10^5$</td>
</tr>
</tbody>
</table>

Table 6.1: Penetration depth in $Si$, $GaSb$ and $InGaAs$ for lasers $658\text{nm}$ and $980\text{nm}$
References


