The study of near-interface oxide traps and tunneling in MOS devices with the charge pumping technique

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AUTHOR: Paulsen, Ronald E.

TITLE: The Study of Near-Interface Oxide Traps and Tunneling in MOS Devices With the Charge Pumping Technique

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THE STUDY OF NEAR-INTERFACE OXIDE TRAPS AND TUNNELING IN MOS DEVICES WITH THE CHARGE PUMPING TECHNIQUE

by Ronald E. Paulsen

A Thesis Presented to the Graduate Committee of Lehigh University in Candidacy for the Degree of Master of Science in Electrical Engineering

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This thesis is accepted and approved in partial fulfillment of the requirements for the Master of Science.

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\( A_G \) \hspace{1cm} \text{area of the gate (cm}^2\text{)}

\( D_{it}(E_t) \) \hspace{1cm} \text{interface state density (cm}^{-2}\text{eV}^{-1}\text{)}

\( D_{it} \) \hspace{1cm} \text{average density of interface traps (cm}^{-2}\text{eV}^{-1}\text{)}

\( D_{it}(E_t, t) \) \hspace{1cm} \text{density of occupied interface traps (cm}^{-2}\text{eV}^{-1}\text{)}

\( E \) \hspace{1cm} \text{energy (J)}

\( E_{CS} \) \hspace{1cm} \text{conduction band energy at the Si-SiO_2 interface (eV)}

\( E_{em,e} \) \hspace{1cm} \text{energy of onset of electron emission (eV)}

\( E_{em,h} \) \hspace{1cm} \text{energy of onset of hole emission (eV)}

\( E_F \) \hspace{1cm} \text{Fermi level (eV)}

\( E_{F,inv} \) \hspace{1cm} \text{Fermi energy in inversion (eV)}

\( E_{F,acc} \) \hspace{1cm} \text{Fermi energy in accumulation (eV)}

\( E_i \) \hspace{1cm} \text{intrinsic energy level (eV)}

\( E_{is} \) \hspace{1cm} \text{intrinsic energy level at the Si-SiO_2 interface (eV)}

\( E_m(t) \) \hspace{1cm} \text{time dependent quasi Fermi level (eV)}

\( E_m(0) \) \hspace{1cm} \text{steady state/non steady state transition point energy (eV)}

\( E_t \) \hspace{1cm} \text{interface trap energy (eV)}

\( E_{VS} \) \hspace{1cm} \text{valence band energy at the Si-SiO_2 interface (eV)}

\( E_1 \) \hspace{1cm} \text{lowest trap energy level filled with an electron (eV)}

\( e_n^{-} \) \hspace{1cm} \text{emission coefficient of electrons (sec}^{-1}\text{)}

\( e_p^{+} \) \hspace{1cm} \text{emission coefficient of holes (sec}^{-1}\text{)}

\( f \) \hspace{1cm} \text{frequency of charge pumping waveform (Hz)}

\( f_{\text{break}} \) \hspace{1cm} \text{breakpoint frequency (Hz)}

\( f(E_t, t) \) \hspace{1cm} \text{non steady state occupancy function}

\( \hbar \) \hspace{1cm} \text{Planck's constant (J} \cdot \text{sec)}

\( I_B \) \hspace{1cm} \text{current measured through the bulk (A)}
$I_{cp}$ charge pumping current (A)
$I_{(cp)peak}$ peak value of the charge pumping current (A)
$I_{S/D}$ current measured through the source and drain (A)
$I_1$ electron capture current component (A)
$I_2$ electron emission current component (A)
$I_3$ hole capture current component (A)
$I_4$ hole emission current component (A)
$k$ Boltzmann's constant (eV/K)
$l$ angular momentum quantum number
$\hat{L}$ angular momentum operator
$M_{AI}$ matrix element of tunnel transition (eV)
$m_1^*$ effective mass of an electron in SiO$_2$ (kg)
$m_2^*$ effective mass of an electron in Si (kg)
$N_C$ conduction band effective density of states (cm$^{-3}$)
$N_V$ valence band effective density of states (cm$^{-3}$)
$n_i$ intrinsic carrier density (cm$^{-3}$)
$n_s$ surface concentration of minority carriers (cm$^{-2}$)
$n_{it}^-(t)$ carrier density (electrons) in the traps (cm$^{-2}$)
$n_{it}^+(t)$ carrier density (holes) in the traps (cm$^{-2}$)
$p$ transition probability (cm$^{-1}$t$^{-1}$)
$P$ total transition probability (t$^{-1}$)
$P_l^m(\theta, \phi)$ associated Legendre functions
$Q_{it}$ total interface trapped charge density (C/cm$^2$)
$Q_{cp}$ charge recombined per cycle (C)
$q$ electronic charge (C)
$R(r)$ radial portion of the electronic wave function
$R_l(r)$ radial portion of the electronic wave function leaving the interface
$T$ period of the charge pumping waveform (sec), temperature (K)
$t$ time (sec)
$t_{em,e}$ time for emission of electrons (sec)
$t_{em,h}$  time for emission of holes (sec)
$t_f$  fall time of the charge pumping waveform (sec)
$t_{ox}$  thickness of the dielectric (cm)
$t_r$  rise time of the charge pumping waveform (sec)
$V(r)$  potential energy of the system (J)
$V_B$  lowest level of the charge pumping waveform (V)
$V_{FB}$  flatband voltage (V)
$V_G$  gate voltage (V)
$V_{TH}$  threshold voltage (V)
$v_{th}$  thermal velocity (cm/sec)
$V_\delta$  strength of the trap potential well (eV)
$V_{EI}$  strength of the interface trap potential well (eV)
$Y_l^m(\theta, \phi)$  spherical harmonics
$\Delta V_G$  amplitude of the charge pumping waveform (V)
$\Delta \psi_e$  electron capture surface potential range (V)
$\Delta \psi_{ee}$  electron emission surface potential range (V)
$\Delta \psi_h$  hole capture surface potential range (V)
$\Delta \psi_{he}$  hole emission surface potential range (V)
$\lambda$  angular momentum eigenvalue
$\phi_B$  Si and SiO$_2$ conduction band barrier height (eV)
$\psi_S$  surface potential (V)
$\psi(r, \theta, \phi)$  electron wave function (cm$^{-\frac{1}{2}}$)
$\rho(E)$  final energy distribution of states (cm$^{-1}$eV$^{-1}$)
$\rho_{ot}(E, z)$  volume density of oxide traps (cm$^{-3}$eV$^{-1}$)
$\rho_{ot}(E, z, i)$  volume density of occupied oxide traps (cm$^{-3}$eV$^{-1}$)
$\sigma_n$  trap capture cross section for electrons (cm$^2$)
$\sigma_n^0$  equilibrium trap capture cross section for electrons (cm$^2$)
$\sigma_n(E_t)$  trap capture cross section for electrons distributed in energy (cm$^2$)
$\sigma_p$  trap capture cross section for holes (cm$^2$)
$\sigma_p^0$  equilibrium trap capture cross section for holes (cm$^2$)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>$\tau(E_t, x)$</td>
<td>trap-to-trap tunneling time constant (sec)</td>
</tr>
<tr>
<td>$\tau_{ep}$</td>
<td>time constant of hole emission (sec)</td>
</tr>
<tr>
<td>$\tau_0$</td>
<td>intrinsic level emission time constant (sec)</td>
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<tr>
<td>$\tau_{tn}$</td>
<td>time constant of electron capture (sec)</td>
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Abstract

In this study charge pumping has been utilized to examine near-interface oxide traps in irradiated MOSFET devices and in polySilicon-Oxide-Nitride-Oxide-Silicon (SONOS) nonvolatile semiconductor memory devices. The technique of charge pumping is used frequently in the study of interface traps by applying a square wave to the gate of the device and measuring the resulting current through the source and drain. A relationship between the charge pumping current \( (I_{cp}) \) and the average interface state density \( (D_{it}) \) has been developed previously. This relationship shows \( I_{cp} \) to be directly proportional to the frequency \( (f) \) of the applied square wave. If the charge recombined per cycle \( (Q_{cp} = I_{cp}/f) \) is examined, however, then no frequency dependence is observed.

During exposure to ionizing irradiation from a \( ^{60}\text{Co} \) source, interface states as well as traps located spatially near the interface (i.e. near-interface oxide traps) are formed. In the presence of near-interface oxide traps, a distinct rise in \( Q_{cp} \) is observed as the frequency of the applied square wave is lowered. A trap-to-trap tunneling mechanism is proposed to account for this low frequency increase in \( Q_{cp} \).

In an attempt to understand the observed increase in charge pumped, SONOS devices were fabricated with a nitride trapping layer deposited on an ultra-thin initial oxide grown in-situ in the LPCVD nitride reactor tube. The silicon-nitride dielectric is known to trap charge which is tunneled from the semiconductor. Thus, a high density of traps may be placed very close to the interface. The charge recombined per cycle on ultra-thin tunnel oxide SONOS structures exhibits similar characteristics to the irradiated devices indicating electrical communication between interface and near-interface traps is a plausible explanation for the increased charge observed.

A trap-to-trap tunneling time constant expression has been developed previously.
which shows the time constant is inversely proportional to $D_{rr}$ and exponentially dependent on the tunneling distance. Since the tunneling distance for SONOS devices is known a theoretical time constant may be calculated. If a time constant is defined as the reciprocal of the frequency at which the $Q_{cp}$ vs. $\log f$ curve deviates from classical theory, then a measured time constant may be determined. Excellent agreement between the theoretical and measured time constants supports the proposed trap-to-trap tunneling model.
Chapter 1

Introduction

The material presented in this thesis originates from experiments which were designed to study the radiation hardness of Metal-Oxide-Silicon-Field-Effect-Transistor (MOSFET) gate dielectrics to the build up of positive fixed charge and interface states during exposure to ionizing radiation. Dual-dielectric 'stacked' gate insulators comprised of oxide/nitride (SiO$_2$/Si$_3$N$_4$) were investigated. Refinement and optimization of techniques for the fabrication of such thin dual-dielectric gate insulators coupled with a thorough investigation of the effects of ionizing radiation provided a 'feedback' system utilizing the electrical characteristics of the irradiated devices to guide the optimization of the dual-dielectric insulator. Examination of the irradiated pure oxide control devices showed an anomalous effect related to the charge pumping technique which was investigated for this work.

MOSFETs irradiated under a positive gate bias build up a high density of traps located spatially near the Si-SiO$_2$ interface in the bulk of the oxide. During a charge pumping experiment these near-interface oxide traps communicate electrically with the interface traps resulting in an additional charge pumping current component. When MOS structures are exposed to ionizing radiation, electron and hole pairs are generated as shown in Figure 1.1. The electrons which are very mobile in the oxide, are swept out of the dielectric when a positive gate bias is applied to the sample. However, holes, with much less mobility than electrons, move toward the Si-SiO$_2$ interface and become trapped[1]. Therefore, devices irradiated under positive gate bias build up more interface states, provided no attempt has been made to minimize the effects of ionizing radiation, than when irradiated under a negative gate bias. Holes and/or positive ions (H$^+$) breaking Si-H bonds are thought to be responsible
Figure 1.1: The band diagram for an n$^+$ doped polysilicon-oxide-silicon (MOS) structure with incident ionizing radiation. The radiation produces electron-hole pairs in the oxide. Electrons are swept from the oxide, while the holes trap and migrate near the interface when a positive gate bias is applied during irradiation.

for the buildup of interface traps[2, 3]. Some holes create the interface states while other holes form near-interface oxide traps which are located within a tunneling distance of the interface.

These near-interface oxide traps may exchange charge with the interface states at very low frequencies creating additional current components observed as noise[4]. In this work an interface trap to bulk dielectric trap (trap-to-trap) tunneling mechanism is proposed to account for this additional current. For example, an electron in the inversion layer first fills an empty interface trap and subsequently tunnels to a trap in the bulk of the oxide. Additionally, when the device is driven into accumulation, this electron may back-tunnel from the bulk oxide trap to the interface trap where it recombines with a substrate hole. Alternatively, when the device is
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held in accumulation, a hole will fill an empty interface trap and may subsequently tunneling to a bulk oxide trap. When the device is pulsed into inversion this hole may back-tunnel to the interface where it recombines with an electron from the inversion layer.

Since charge pumping is a technique used frequently to study the interface and since the electric fields applied during the experiment are relatively low, an interface trap to near-interface oxide trap tunneling mechanism is proposed. The charge pumping technique is a relatively simple measurement technique which can provide information on, among other device characteristics, the density of interface traps, \( D_{it} \). A net charge pumping current is produced when a device is pulsed from accumulation to inversion and back to accumulation. Ideally, the pulsing of the gate yields no net transfer of charge since the number of carriers entering the channel is the same as the number of carriers leaving the channel. Thus, no current would be produced. However, a net charge transfer is observed experimentally resulting in a charge pumping current, \( I_{cp} \), due to the recombination of minority carriers with majority carriers trapped at the interface\[5\]. The charge pumping current is observed to be directly proportional to the frequency of the applied gate pulse; however, the charge recombined per cycle, \( Q_{cp} \), is found to be independent of frequency when a square waveform is applied\[6\]. When charge pumping measurements are made on the samples which are irradiated with a positive bias the charge recombined per cycle does not remain constant. Instead \( Q_{cp} \) increases with decreasing frequency. The additional charge recombination is attributed to communication between interface traps and near-interface oxide traps via a quantum mechanical tunneling mechanism.

Support for the proposed mechanism has been provided by fabricating and testing devices with a silicon nitride layer placed very close to the Si-SiO\(_2\) interface. It is well known the silicon nitride dielectric can trap and store charge, which is tunneled from the semiconductor. Devices with a silicon nitride layer, known as Metal-Nitride-Oxide-Semiconductor (MNOS) or poly Silicon-Oxide-Nitride-Oxide-Semiconductor (SONOS) devices, can act as nonvolatile memory elements\[7, 8\]. The
energy band diagram for a memory element utilizing the trapping properties of silicon nitride is shown in Figure 1.2. The devices used in this study have a 48Å silicon nitride dielectric (LPCVD; 10:1, NH$_3$:SiCl$_2$H$_2$ at 725°C) deposited on a 12Å ultra-thin tunnel oxide (formed during the 15 minute warm-up period in the CVD nitride reactor tube) in the channel region. The blocking oxide (LPCVD; 10:1, N$_2$O:SiCl$_2$ at 725°C followed by a 900°C steam oxidation for densification) placed on the nitride layer is 30Å. See Appendix A for the complete fabrication sequence. In contrast to the ultra-thin oxide SONOS devices examined in this work, conventional SONOS structures have tunnel oxides of ~20Å to improve retention characteristics of the stored charge.

The ultra-thin tunnel oxide SONOS devices exhibit a frequency dependent charge recombined per cycle indicating communication between the nitride traps and the channel region. In a manner similar to the positively biased irradiated devices, electrons are able to fill the interface traps and subsequently tunnel into the nitride traps when the device is held in inversion for longer periods of time. Likewise, when driven into accumulation the electrons back tunnel to the interface and recombine with substrate holes.

The study of near-interface oxide traps and the mechanism of communication between the channel region and the bulk dielectric traps is important for device reliability considerations. Near-interface oxide traps can cause trapping-induced dielectric relaxation effects in MOS devices as well as threshold voltage shifts in MOSFETs. The charge which is trapped may have little or no effect on the operation of digital circuitry where the noise margin is sufficient to absorb any related threshold voltage shifts. However, performance of high precision analog circuits, such as switch capacitor filters, charge-coupled devices, charge redistribution analog-to-digital converters, and sample-and-hold circuits, could be greatly effected by charge storage producing hysteresis, charge transfer inefficiencies, charge redistribution errors, and settling time inaccuracies[9]. In addition, the tunneling mechanism responsible for communication between the traps is also of importance as it yields information on the mechanism for charge storage and retention for SONOS and MNOS nonvolatile
Figure 1.2: The band diagram of a SONOS memory device with an $n^+$ doped poly gate. The nitride layer has a high density of trapping centers. Charge may communicate between the bulk nitride traps and the interface traps in a manner similar to the un-hardened irradiated oxide sample. As the applied field is increased the energy bands show additional bending bringing more of the nitride traps closer to the interface. Unlike conventional SONOS, with tunneling oxide thicknesses of 20Å, this device has an ultra-thin tunnel oxide of 12Å.
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memory devices.

The material presented in this thesis covers the development of the classical charge pumping theory, as well as the development of the theoretical trap-to-trap tunneling time constant. Experimental results indicate electrical communication between interface traps and near-interface oxide traps. Finally, a quantum mechanical charge pumping model is proposed for further research.
Chapter 2

Charge Pumping

The technique of charge pumping is a widely used measurement technique for characterizing the interface of MOS structures. There are a number of variations of the charge pumping experiment which produce a wide variety of information regarding the interface. Conventional (bi-level) charge pumping can yield information on the average density of interface states, $D_{it}$, and the geometric mean of the capture cross sections, $\sqrt{\sigma_n \sigma_p}$[5, 6]. A technique called pulsed interface probing has also been used to obtain mid-gap values for $D_{it}$ and $\sigma$[10]. A third technique, tri-level charge pumping, seems to be the most powerful since it allows determination of the energy distribution of the density of interface states, $D_{it}(E)$, and the energy distributions of the electron and hole capture cross sections, $\sigma_n$ and $\sigma_p$, respectively[11, 12]. This chapter will discuss the bi-level charge pumping experimental setup and theory.

2.1 Measurement Technique

One of the advantages of utilizing charge pumping to characterize the interface is the relative ease in experimentation and analysis. Unlike other techniques for determining interface trap density, such as capacitance-voltage (C-V) techniques which require either generation of an ideal C-V curve for comparison to the measured curve or multiple measurement techniques[13, 14, 15, 16], charge pumping requires only the measurement of the charge pumping current to determine $D_{it}$. Figure 2.1 shows the experimental setup used for this measurement. A square voltage waveform of amplitude $\Delta V_G$ with respect to the base voltage, $V_B$, is applied to the gate of
CHAPTER 2. CHARGE PUMPING

Figure 2.1: The charge pumping experimental setup is shown with the applied gate voltage waveform. The applied signal generates electron and hole currents which average to a non-zero current component through one complete pulse. As the frequency of the applied signal is increased the current measured likewise increases. This non-zero component is the measured charge pumping current, $I_{cp}$, which is directly proportional to $D_{it}$.

The device. This applied waveform generates a charge pumping current which is measured through the common source and drain. Effectively, the source, drain, and substrate are tied together and grounded through the virtual short property of the op amp. With each complete pulse the electron and hole current components average out, unless there is some net loss of charge via a recombination process with the interface. The net loss of charge is measured as $I_{cp}$ and is directly proportional to $D_{it}$.

Typically, the average density of interface traps is obtained by sweeping the base level of the applied pulse from deep accumulation to strong inversion with an amplitude greater than the bandgap. In so doing, the pulse is swept through the
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entire bandgap of the semiconductor. The result of the measurement is shown in Figure 2.2 where the charge pumping current is plotted as a function of the base level. The curve is intuitively correct, when the base level is in deep accumulation, the pulse reaches a peak value insufficient to bring the device out of accumulation, i.e. the Fermi level is pinned at the valence band. Therefore, it is not favorable for electrons to trap and recombine with the holes in the interface. Since there is no recombination all the holes which entered the interface remain trapped and no net current is observed. As the base level is increased from accumulation, the Fermi level is swept to a position where some recombination of electrons with holes occurs. The recombination gives rise to a current which continues to increase until the entire bandgap is being spanned and a peak charge pumping current is observed. It is the peak charge pumping current which is proportional to the average density of interface traps. Similarly, as the base level is increased, holes are unable to fill the entire interface reducing the number of carriers which recombine, thereby reducing the measured current.

2.2 Theoretical Analysis

In order to gain insight into the charge pumping technique an expression for the charge pumping current will be developed following Groeseneken et al.[6] and Simmons and Wei[17]. From the charge pumping expression the charge recombined per cycle, $Q_{cp}$, is found to be independent of frequency. However, it is valid only for samples with a low density of near-interface oxide traps. In the presence of a high density of near-interface oxide traps an additional charge pumping current is produced leading to a frequency dependent $Q_{cp}$. 
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Figure 2.2: When the charge pumping current is measured as a function of the base voltage level the curve above results. The peak value of the charge pumping current, $I_{cp(peak)}$, is directly proportional to $\overline{D_{it}}$. As the applied waveform is swept from deep accumulation to strong inversion the entire bandgap is examined. Inset shows the parameters of the applied voltage waveform.
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2.2.1 Processes

In the previous section the processes involved in charge pumping were briefly discussed. The discussion in this section will begin by examining more closely these processes. Figure 2.3 illustrates the applied gate voltage as a function of time with the individual processes labeled and the corresponding band diagrams given. The parameters of the pulse are the base voltage level, $V_B$, the pulse height, $\Delta V_G$, the period, $T = 1/f$, and the rise and fall times, $t_r$ and $t_f$, respectively.

Assuming n-channel devices the following processes are observed:

1. Accumulation
   In this region all the interface traps are filled with electrons below the Fermi-level and filled with holes above it. The states are in equilibrium with the energy bands such that there is no net change in the electron, hole, or trap currents.

2. Approaching Flatband
   During this time the surface potential, $\psi_S$, is changing. In order to maintain dynamic equilibrium, holes are emitted back to the valence band (i.e. more electrons fill traps). This occurs as long as the rate of emission of holes from trap levels less than a few $kT$, where $k$ is Boltzmann's constant and $T$ is the absolute temperature, below the Fermi level is greater than the capture rate of electrons by these same levels, which can be stated in equation form as follows:

   $$\left( \frac{dQ_{it}}{dt} \right)_{emp} > \left( \frac{dQ_{it}}{dt} \right)_{ssp} \quad (2.1)$$

   where the rate of change of the total trapped charge density corresponding to hole emission is given by:

   $$\left( \frac{dQ_{it}}{dt} \right)_{emp} = q \frac{dn_{it}^+(t)}{dt}$$
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Figure 2.3: The applied gate voltage as a function of time for the charge pumping experiment. For n-channel devices the base level of the pulse corresponds to accumulation and the peak of the pulse corresponds to inversion. As the pulse rises from accumulation through inversion the levels appropriate to reach flatband and threshold of weak inversion are achieved. The period, $T$, and the rise and fall times, $t_r$ and $t_f$, respectively, are illustrated. The band diagrams correspond to the processes observed during charge pumping.
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with \( n^+_t(t) \) being the carrier density (holes) in the traps. The rate of change of total trapped charge density required to maintain equilibrium is given by:

\[
\left( \frac{dQ_{it}}{dt} \right)_{ssp} = q^2 D_{it} \frac{d\psi}{dt}
\]

3. Flatband

The transition point between steady state and non-steady state is near flatband. After the transition point is crossed the non-steady state emptying of the traps is controlled by the hole emission which is governed by a time dependent Fermi-Dirac distribution occupancy function. Equation (2.1) no longer holds. The rate of emission of holes from trap levels a few \( kT \) below the Fermi level is less than the capture of holes or

\[
\left( \frac{dQ_{it}}{dt} \right)_{emp} < \left( \frac{dQ_{it}}{dt} \right)_{ssp}.
\]

4. Depletion

The depletion region corresponds to the non-steady state regime. Since the concentration of free carriers is small, the trapping time constant is controlled by the time constant of hole emission, which is given by

\[
\tau_{ep} = \frac{1}{e_p^+}
\]

where \( e_p^+ \) is the emission coefficient for donor traps,

\[
e_p^+ = \sigma_p^0 v_{th} N_V e^{-(E_T - E_{VS})/kT}
\]

where \( \sigma_p^0 \) is the equilibrium capture cross section for holes, \( v_{th} \) is the thermal velocity, \( N_V \) is the density of states in the valence band, \( E_T \) is the energy of the trap, and \( E_{VS} \) is the energy of the valence band at the surface.

5. Rising to Threshold of Weak Inversion

As the pulse approaches the threshold of weak inversion the trapping time constant for electrons, \( \tau_{in} \), becomes smaller until electrons are captured
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by traps concurrently occupied by holes resulting in recombination. The trapping time constant is given by:

$$\tau_{tn} \approx \frac{1}{\sigma_n^0 v_{th} n_s}$$

where $\sigma_n^0$ is the equilibrium capture cross section and $n_s$ is the surface concentration of minority carriers. A second transition point between non-steady state emission and steady state emission is near the threshold of weak inversion.

6. Inversion

As with the accumulation case the interface states are in equilibrium with the energy bands when in strong inversion. Thus, there is no net change of the electron, hole or trap currents. All states above the Fermi level are assumed to be empty while all states below are assumed to be full indicating all interface traps are full.

7. Descending to Threshold of Weak Inversion

In a manner similar to holes on the rising edge of the pulse, the electrons are emitted from traps in a steady state process. Similar to Equation (2.1), the condition

$$\left(\frac{dQ_{it}}{dt}\right)_{enn} > \left(\frac{dQ_{it}}{dt}\right)_{ssn}$$

is satisfied such that the rate of emission of electrons from trap levels greater than a few $kT$ above the Fermi level is greater than the capture rate of holes by these levels. The emission rate of trapped electrons and the rate of change of total trapped charge density required to maintain steady state are given, respectively, by the following:

$$\left(\frac{dQ_{it}}{dt}\right)_{enn} = -q \frac{dn_{it}^-(t)}{dt}$$

and

$$\left(\frac{Q_{it}}{dt}\right)_{ssn} = -q^2 D_{it} \frac{d\psi_s}{dt}.$$
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8. Depletion
Near the threshold for weak inversion is the transition point between steady state and non-steady state where Equation (2.2) no longer holds, such that

\[
\frac{dQ_{it}}{dt}_{emn} < \frac{dQ_{it}}{dt}_{sen}.
\]

Once in the depletion region the emission of electrons becomes non-steady state in nature such that the rate of emission of electrons is much less than the capture of holes resulting in recombination.

9. Descending to Flatband
As the pulse nears flatband the transition point between non-steady state and steady state is reached sending the system back into equilibrium. At this point the hole capture rate is less than the electron emission rate such that holes trap and fill all the interface traps. The pulse continues to descend until accumulation is reached and the process starts over.

It is evident from the above qualitative analysis, current components are observed due to the non-steady state processes. In order to quantify these components non-steady state charge dynamics is applied.

2.2.2 Resultant Current Components

Based on the previous qualitative analysis it is observed that the rising edge of the applied gate pulse produces a hole current component and the falling edge produces an electron current. If the density of interface traps is assumed to be uniform (i.e. \( D_{it}(E) = \overline{D}_{it} \)) then these current components can be written down explicitly noting there is only current over the range of surface potentials corresponding to nonequilibrium. The electron currents are given as:

\[
I_1 = -q^2\overline{D}_{it}A_G\Delta\psi_e f
\]
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and

\[ I_2 = q^2 \overline{D_{it}} A_G \Delta \psi_{ee} f \]

where \( q \) is the charge on an electron, \( A_G \) is the area under the gate, \( \Delta \psi_e \) and \( \Delta \psi_{ee} \) are the surface potential ranges corresponding to electron capture and emission, respectively. The electron capture current, \( I_1 \), corresponds to regions 4-5 and the electron emission current, \( I_2 \), corresponds to regions 7-8 of Figure 2.3. Similarly, the hole current components are given as:

\[ I_3 = q^2 \overline{D_{it}} A_G \Delta \psi_{he} f \]

and

\[ I_4 = -q^2 \overline{D_{it}} A_G \Delta \psi_{he} f \]

where \( \Delta \psi_h \) and \( \Delta \psi_{he} \) are the surface potential ranges for capture and emission of holes, respectively. The hole capture current, \( I_3 \), corresponds to region 9 and the hole emission current, \( I_4 \), corresponds to regions 1-4. Figure 2.4 demonstrates the resulting currents for an n-channel device.

From the experimental setup shown in Figure 2.1 the charge pumping current is seen to be equivalent to the current through the source and drain,

\[ I_{cp} = I_{S/D}. \]

In Figure 2.4 this current is seen to be the sum of the electron capture and emission components,

\[ I_{S/D} = I_1 + I_2. \]

Substituting in the known quantities for capture and emission of electrons the following is observed:

\[ I_{cp} = q^2 \overline{D_{it}} A_G f (\Delta \psi_{ee} - \Delta \psi_e). \quad (2.3) \]

The charge pumping current may also be measured through the bulk of the device with the source and drain grounded. This gives a charge pumping current equal to the current measured through the bulk,

\[ I_{cp} = I_B, \]
Figure 2.4: The current components which result from charge pumping. The electron capture and emission components are represented by $I_1$ and $I_2$, respectively. Similarly, the hole capture and emission current components are given by $I_3$ and $I_4$, respectively.
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Figure 2.5: From the energy band diagram at the surface the range of surface potentials corresponding to emission and capture of electrons, $\Delta \psi_{ee}$ and $\Delta \psi_{e}$, respectively, and to emission and capture of holes, $\Delta \psi_{he}$ and $\Delta \psi_{h}$, respectively, can be identified. The assumption that the threshold voltage is close to the Fermi level has been made.
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where the bulk current is the sum of the hole capture and emission components,

\[ I_B = I_3 + I_4, \]

as illustrated in Figure 2.4. This gives rise to a charge pumping current of

\[ I_{cp} = q^2 \overline{D}_{it} A_G f(\Delta \psi_{he} - \Delta \psi_h). \]  

(2.4)

The range of surface potential over which capture and emission processes occur can best be defined on an energy band diagram at the surface of the device, as seen in Figure 2.5. Figure 2.5 shows the energy range for which non-steady state electron capture and emission takes place producing recombination of charge and a net charge pumping current. This range,

\[ q(\Delta \psi_{ee} - \Delta \psi_e) = E_{em,h} - E_{em,e}, \]

when substituted into Equation (2.3) yields the following:

\[ I_{cp} = q \overline{D}_{it} A_G f(E_{em,h} - E_{em,e}). \]  

(2.5)

Similarly, the hole processes exhibit an energy range for non-steady state capture and emission which is

\[ q(\Delta \psi_h - \Delta \psi_{he}) = -(E_{em,h} - E_{em,e}). \]

Substitution into Equation (2.4) produces a charge pumping current,

\[ I_{cp} = -q \overline{D}_{it} A_G f(E_{em,h} - E_{em,e}), \]  

(2.6)

which is equal and opposite the electron current components.

In order to fully understand Equation (2.5) or (2.6) the energy levels corresponding to the onset of hole emission and the onset of electron emission must be determined. Since these processes occur in a non-steady state fashion, non-steady state charge dynamics must be implemented. The energy band diagram shown in Figure 2.6 illustrates the energy levels referred to in the forthcoming analysis. The
Figure 2.6: For the analysis of non-steady state charge dynamics the notation of the energy band diagram is used. $E_t$ corresponds to the energy level of the trap being examined and $E_1$ is the lowest trap energy level filled.

energy level of the interface trap being examined is given by $E_t$ and the lowest filled trap is given by $E_1$. Two initial assumptions will be made. First, assume acceptor type traps and second, assume the density of interface traps and the capture cross sections are energy independent and are given by

$$D_{it}(E_t) \approx \overline{D_{it}}$$

and

$$\sigma_n(E_t) \approx \sigma_n,$$

respectively. Acceptor traps have been shown to be a good assumption for interface traps in the upper half of the bandgap. Even if amphoteric traps are assumed, the donor like traps will be far beneath the conduction band, in the bottom half of the bandgap, and will not affect the analysis. The assumption of energy independent interface trap density and capture cross section is valid except near the band edges.

The rate of change of trapped charge, $dn_{it}/dt$, in the region of interest is governed by the emission time. This implies the net rate of change is given by the sum over
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All the energy levels of the product of the trapped charge density, \( D_{it}^- (E_t, t) \), and the emission coefficient of electrons, \( e_n^- (E_t) \). Since there is a continuous distribution of interface traps in energy the net rate of change of occupied traps is given by:

\[
\frac{dn_{it}^-}{dt} = - \int_{E_i}^{E_C} D_{it}^- (E_t, t) e_n^- (E_t) dE_t. \tag{2.7}
\]

Substitution of

\[
n_{it}^- = \int_{E_i}^{E_C} D_{it}^- (E_t, t) dE_t
\]

into Equation (2.7) produces:

\[
\int_{E_i}^{E_C} \left[ \frac{dD_{it}^- (E_t, t)}{dt} + D_{it}^- (E_t, t) e_n^- (E_t) \right] dE_t = 0. \tag{2.8}
\]

In order to satisfy Equation (2.8) the integrand must be zero. Solving the differential equation in the integrand produces an expression for the number of occupied traps:

\[
D_{it}^- (E_t, t) = D_{it}^- (E_t) e^{-e_n^- (E_t) t}.
\]

Thus, the trapped charge is seen to be governed by a non-steady state occupancy function given by:

\[
f(E_t, t) = \frac{D_{it}^- (E_t, t)}{D_{it}^- (E_t)} = e^{-e_n^- (E_t) t}, \tag{2.9}
\]

where the emission coefficient is given by[18]

\[
e_n^- (E_t) = v_{th} \sigma_n N_C e^{-(E_C - E_t)/kT}
\]

and \( N_C \) is the effective density of states in the conduction band. The non-steady state occupancy function of Equation (2.9) is plotted in Figure 2.7 as a function of trap energy with time as a parameter. Since this function behaves as a time dependent quasi-Fermi function, the midpoint of the occupancy function gives rise to a time dependent quasi-Fermi level of energy \( E_m(t) \) defined below:

\[
e^{-\frac{t}{\tau_0}} e^{-(E_t - E_m(t))/kT} \Delta \frac{1}{1 + e^{(E_t - E_m(t))/kT}}
\]

where

\[
\tau_0 = \left( v_{th} \sigma_n n_i \right)^{-1}
\]

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Figure 2.7: Equation (2.9) is plotted as a function of trap energy with time as a parameter. Notice the resemblance to a quasi-Fermi function. Due to this resemblance the function is considered to have a time-dependent quasi-Fermi level of energy $E_m(t)$.

is the intrinsic emission time constant and

$$n_i \triangleq N_C e^{-(E_C - E_i)/kT}$$

is the intrinsic carrier concentration. The occupancy function may be considered to allow all traps below $E_m(t)$ to be filled and all traps above $E_m(t)$ to be empty. Thus, Equation (2.7) may be written as

$$- \frac{dn_{it}}{dt} = D_{it} \sigma_n v_{th} N_C \int_{E_i}^{E_m(t)} e^{-(E_C - E_t)/kT} dE_t$$

which upon integration yields

$$- \frac{dn_{it}}{dt} = D_{it} \sigma_n v_{th} N_C kT e^{-E_C/kT} (e^{E_m(t)/kT} - e^{E_1/kT}). \quad (2.10)$$

The number of filled traps can be found by integrating, with respect to trap energy, the density of interface traps to obtain

$$n_{it}(t) = \int_{E_i}^{E_C} D_{it}^{-1}(E_i, t) dE_t = \int_{E_i}^{E_m(t)} D_{it}(E_t) dE_t,$$
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or

\[ n_{ii}(t) = \overline{D_{ii}}[E_m(t) - E_1]. \]  

Equation (2.11) can be differentiated with respect to time and substituted into Equation (2.10) to obtain an expression for the time rate of change of the non-steady state quasi-Fermi energy:

\[ \frac{dE_m(t)}{dt} = vth \sigma_n N_C kT e^{-Ec/kT} (e^{E_m(t)/kT} - e^{E_1/kT}). \]

The preceding expression may be simplified by multiplying the right hand side of the equation by \( e^{(E_1-E_i)/kT} = 1 \) resulting in the following:

\[ \frac{dE_m(t)}{dt} = -\frac{kT}{\tau_0} (e^{E_m(t)-E_i)/kT} - e^{(E_1-E_i)/kT}). \]  

The time dependence of the non-steady state quasi-Fermi level is obtained by solving Equation (2.12). The solution to Equation (2.12) is shown in Appendix B to be

\[ E_m(t) = E_1 - kT \ln\left[1 - (1 - e^{(E_1-E_m(0))/kT}) e^{-\frac{1}{\tau_0} e^{(E_1-E_i)/kT}} \right] \]  

where \( E_m(0) \) is the initial equilibrium Fermi energy. For electron emission the equilibrium Fermi energy corresponds to the Fermi level of inversion, i.e. \( E_m(0) \approx E_{F,inv} \).

On the falling edge of the applied pulse non-steady state conditions exist when the system enters depletion. Once flatband is reached the system returns to steady state indicating the lowest electron filled trap which is pumped is near midgap or the intrinsic energy level. Similarly, for holes the highest filled level is close to the intrinsic level. Therefore, Equation (2.13) can be written as

\[ E_m(t) = E_i - kT \ln\left[1 - (1 - e^{(E_i-E_{F,inv})/kT}) e^{-\frac{1}{\tau_0} e^{(E_i-E_i)/kT}} \right] \]  

where the assumption \( E_i \approx E_{F,inv} \) has been made.

For bi-level charge pumping in n-channel MOSFETs the emission of holes corresponds to the leading edge of the pulse, whereas, for electron emission the trailing edge of the pulse is of importance. Thus, the time dependence of the quasi Fermi
level is controlled by the rise and fall times. In order to simplify Equation (2.14) assume \( t \ll \tau_0 \), where

\[
\tau_0 = \frac{1}{v_{th} \sigma_n n_i} \approx 100 \text{msec}
\]

with \( v_{th} \sim 10^7 \text{ cm/sec} \), \( \sigma_n \sim 10^{-16} \text{ cm}^2 \), and \( n_i \sim 10^{10} \text{ cm}^{-3} \). Thus, the rise and fall times must be kept less than 10 msec in order to maintain the validity of the assumption. A similar assumption is also made in tri-level charge pumping where the step time is kept less than 10 msec in order to insure the validity of the approximation. From a physical perspective, the rise and fall times must be significantly less than the time constant for emission at the intrinsic level in order to control the emission process.

Maintaining \( t \ll \tau_0 \), the exponential in the logarithm term can be approximated by the first two terms of the power series expansion. This reduces the argument of the logarithm to

\[
1 - (1 - \exp[(E_i - E_{F, \text{inv}})/kT]e^{-\frac{t}{\tau_0}}) \approx \frac{t}{\tau_0} + e^{(E_i - E_{F, \text{inv}})/kT}.
\]

Thus, Equation (2.14) can be written as

\[
E_m(t) - E_i = -kT \ln[\frac{t}{\tau_0} + e^{(E_i - E_{F, \text{inv}})/kT}].
\]

This expression written for the quasi-Fermi level energy corresponding to the emission of electrons, \( E_{em,e} \), is

\[
E_{em,e} - E_i = -kT \ln[\frac{t_{em,e}}{\tau_0} + e^{(E_i - E_{F, \text{inv}})/kT}],
\]

where \( t_{em,e} \) corresponds to the time for which emission of electrons takes place, which is a fraction of the fall time;

\[
t_{em,e} = \frac{|V_{FB} - V_{TH}|}{|\Delta V_G|} t_f,
\]

corresponding to Region 7 of the charge pumping pulse.

Similarly, for the emission of holes

\[
E_{em,h} - E_i = kT \ln[\frac{t_{em,h}}{\tau_0} + e^{(E_{F, \text{acc}} - E_i)/kT}]
\]

(2.16)
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where \( E_{F,\text{acc}} \) is the Fermi level corresponding to accumulation and \( t_{em,h} \) is the time for which emission of holes takes place. Similar to electrons, the emission time for holes is a fraction of the rise time;

\[
t_{em,h} = \frac{|V_{FB} - V_{TH}|}{\Delta V_G} t_r,
\]
corresponding to Regions 3-5 of the charge pumping pulse.

The energy levels corresponding to the emission of holes and electrons were determined utilizing the time dependent quasi-Fermi level expression. With these levels established the charge pumping current expression can be written. Subtracting Equations (2.16) and (2.15), and recognizing \( E_{F,\text{acc}} < E_i < E_{F,\text{inv}} \) allows the assumption that the exponential terms are small, produces

\[
E_{em,h} - E_{em,e} \approx 2kT(ln[v_{th}n_i\sqrt{\sigma_p\sigma_n}] + ln[\frac{|V_{FB} - V_{TH}|}{\Delta V_G}\sqrt{t_r t_f}])
\]

Substituting the above quantity into Equation (2.5) the charge pumping current is given by[6]

\[
I_{cp} = qD_{it}fA_G2kT(ln[v_{th}n_i\sqrt{\sigma_p\sigma_n}] + ln[\frac{|V_{FB} - V_{TH}|}{\Delta V_G}\sqrt{t_r t_f}]). \tag{2.17}
\]

The charge pumping current expression shows a direct relationship between the frequency of the pulse and the current measured. As the frequency is increased so does the current. Intuitively, the interface traps will charge and discharge more times for higher frequencies yielding an increase in the amount of charge recom­bined per unit time. If, however, the charge recombined per cycle is examined, no frequency dependence is observed. Recalling \( Q_{cp} = I_{cp}/f \) the expression for the charge recombined per cycle becomes

\[
Q_{cp} = qD_{it}A_G2kT(ln[v_{th}n_i\sqrt{\sigma_p\sigma_n}] + ln[\frac{|V_{FB} - V_{TH}|}{\Delta V_G}\sqrt{t_r t_f}]). \tag{2.18}
\]

Equation (2.18) illustrates the basis of the conventional charge pumping model. That is, regardless of the frequency, the charge recombined each cycle is a constant proportional to the interface trap density, indicating interface traps alone will charge
Figure 2.8: The recombined charge per cycle ($Q_{cp}$) for a non-irradiated MOS device.

A non-irradiated MOSFET is generally characterized by having a relatively low density of near-interface oxide traps. Thus, the conventional charge pumping model may be applied. The charge is constant over a wide range of frequencies consistent with classical charge pumping theory[6].

and discharge once. Thus, irrespective of the frequency of the cycle the charge measured will be proportional to the interface trap density. For devices with a low density of near-interface oxide traps the result has been confirmed experimentally, as shown in Figure 2.8.
Chapter 3
Tunneling

For devices with a low density of near-interface oxide traps the charge recombined per cycle is independent of the frequency, as is shown in Equation (2.18). The development of the charge recombined per cycle expression, outlined in the previous chapter, does not incorporate the possible communication between interface traps and near-interface oxide traps. Thus, the present model for charge pumping is valid only under special conditions. The following chapter will discuss how communication between the interface traps and the oxide traps may take place via quantum mechanical tunneling.

3.1 Trap-to-Trap Tunneling

Charge pumping experiments performed on irradiated devices show a non-linear increase of the charge pumping current which translates into an increase in the charge recombined per cycle for lower frequencies[19]. Figure 3.1 shows the charge recombined per cycle for a device irradiated with an applied field (positive gate voltage) of 4 MV/cm on the gate and a ⁶⁰Co gamma radiation dose of 1 Mrad. An increase in the charge recombined per cycle at frequencies less than 1 kHz is observed. Since radiation is known to cause a build-up of positive charge in the oxide of MOS devices, the presence of a positive electric field would push the holes generated closer to the interface where they form near-interface oxide traps. Therefore, the increased charge recombined per cycle is considered to be a by-product of the tunneling to these oxide traps. The charge pumping current is, thus, the sum of an interface trap
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Figure 3.1: The recombined charge per cycle ($Q_{cp}$) for MOS device W3.5/3.MAA irradiated under a positive bias. In contrast to classical charge pumping theory, the charge is seen to increase at lower frequencies indicating the charge pumping current is the sum of an interface trap component and a bulk oxide trap component.

The mechanism for tunneling to the bulk oxide traps has been proposed to be a trap-to-trap tunneling mechanism. Since the electric fields applied during the charge pumping experiment are relatively low and since the interface traps fill and empty during each cycle it seems natural to consider such a mechanism. For trap-to-trap tunneling to occur an interface trap is filled by an electron when the device is inverted. If the inversion condition is maintained for a sufficiently long period of time\(^1\), then the electron may tunnel into a near-interface dielectric trap. Subsequently, when the device is pulsed into accumulation, holes fill the interface

\(^1\)Contrary to filling an interface trap, where the fill times are very short and determined by the number of available carriers, the filling of near-interface oxide traps may require significantly longer time periods approaching a sizeable fraction of the clock period.
Figure 3.2: The processes of trap-to-trap tunneling may be described as the following: (a) When driven to inversion an electron fills an interface trap and subsequently tunnels to a near-interface oxide trap. (b) When the device is driven back into accumulation the electron is able to back tunnel where it recombines with a substrate hole. A similar process may occur for holes. After a sufficient time the electron back-tunnels to the interface where it recombines with a substrate hole. A similar process may occur for holes. Figure 3.2 illustrates these processes for an electron tunneling to and from a near-interface oxide trap.

In an attempt to provide support for the proposed trap-to-trap tunneling mechanism SONOS devices were fabricated with a trap-rich nitride layer\(^2\) placed 12Å from the interface. As shown in Figure 3.3, these devices exhibited characteristics similar to the irradiated devices indicating communication between the interface traps and the near-interface dielectric traps. Since the distance between the nitride trapping layer and the interface (i.e. the tunnel oxide thickness) is known, with ellipsometry, C-V measurements, and transmission electron microscopy (TEM) analysis, the

\(^2\)The deep level traps in silicon-nitride are thought to be amphoteric and associated with a paramagnetic silicon center back-bonded to three nitrogen centers.
Figure 3.3: The recombined charge per cycle ($Q_{cp}$) for ultra-thin tunnel oxide SONOS device NOX1. The charge increases for lower frequencies confirming that the radiation-induced bulk oxide traps behave in a similar manner to the nitride traps.

3.2 Solution to Schröedinger’s Equation

In order to develop the trap-to-trap tunneling theory, a quantum mechanical formulation must be used. To start, the time-independent Schröedinger equation (TISE) describing an electron trapped in a potential well is written as:

$$ -\frac{\hbar^2}{2m_i} \nabla^2 \psi(r, \theta, \phi) + V(r)\psi(r, \theta, \phi) = E\psi(r, \theta, \phi) $$

(3.1)
where $V(r)$ is the potential energy of the system given by

$$V(r) = \phi_B + E_C - V_\delta(r)$$

where, $\phi_B$ is the energy discontinuity between the conduction band of Si and the conduction band of SiO$_2$, $V_\delta$ is the strength of the potential well, and $\nabla^2$ is the spherical Laplacian operator given by

$$\nabla^2 = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial}{\partial r} \right) + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial}{\partial \theta} \right) + \frac{1}{r^2 \sin^2 \theta} \frac{\partial^2}{\partial \theta^2}.$$ 

The development which follows corresponds to the system shown in Figure 3.4. The trap potentials are assumed to be well described by three dimensional delta functions. The valence band energy is taken as a reference and is assumed to be zero. The trap is located at an energy, $E$, above the valence band and a distance, $x$, from the interface. The electron wave function is approximated with angular momentum quantum number $l = 0$, corresponding to an s-state electron, and the trap is assumed to be at the location $r = 0$.

The solution to the TISE can be obtained in almost any book on quantum mechanics[20]. Applying the separation of variables technique to solve this second order partial differential equation produces both an angular differential equation and a radial differential equation given by

$$\frac{1}{\sin \theta} \frac{d}{d \theta} \left( \sin \theta \frac{d Y}{d \theta} \right) + \frac{1}{\sin^2 \theta} \frac{d^2 Y}{d \phi^2} = -\lambda Y$$

and

$$\frac{d}{dr} \left( r^2 \frac{d R}{dr} \right) + \frac{2m_1^* r^2}{\hbar^2} (E - V(r)) R = \lambda R,$$

respectively. The solution to the angular momentum differential equation (see Appendix C) is the spherical harmonics, $Y_l^m(\theta, \phi)$, with eigenvalue $\lambda = l(l + 1)$.

Using the results of the angular differential equation solution the radial part of the Schröedinger wave equation may be written as

$$- \frac{\hbar^2}{2m_1^*} \left( \frac{1}{r} \frac{d^2}{dr^2} + \frac{l(l + 1)}{r^2} \right) R(r) - V(r) R(r) = E R(r). \quad (3.2)$$
Figure 3.4: The system of delta function trap potential wells in the oxide and at the interface considered for trap-to-trap tunneling. The traps are located at an energy $E$ above the valence band. A distance, $x$, separates the interface trap and the near interface oxide trap. The potential strengths of the interface trap and the oxide trap are given by $V_{\delta I}$ and $V_{\delta}$, respectively. The valence band energy is taken as the reference and is assumed to be zero. The conduction band energy discontinuity between the Si and SiO$_2$ is given by $\phi_B$. 
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Since an s-state was assumed Equation (3.2) can be simplified to

\[ \frac{1}{r} \frac{d^2}{dr^2} (r R(r)) + \frac{2m^*}{\hbar^2} (E - V(r)) R(r) = 0. \]

Outside of the trap, i.e. for \( r > 0 \), the potential energy may be written as, \( V(r) = \phi_B + E_C \), giving rise to the following form of the radial part of Schröedinger's wave equation:

\[ \frac{1}{r} \frac{d^2}{dr^2} (r R(r)) + \eta_1^2 R(r) = 0, \]  

(3.3)

where

\[ \eta_1^2 = (\phi_B + E_C - E) \frac{2m^*}{\hbar^2}. \]  

(3.4)

To solve the differential equation in Equation (3.3) the following change of variable is made: \( u(r) = r R(r) \) or \( R(r) = u(r)/r \). Direct substitution puts Equation (3.3) into the form of the one-dimensional square well problem in quantum mechanics,

\[ \frac{d^2}{dr^2} u(r) + \eta_1^2 u(r) = 0. \]  

(3.5)

The solution to the square well problem is well known to be

\[ u(r) = Ae^{-r} + Be^{r}. \]

Or, after changing back to the original function, the radial solution is:

\[ R(r) = \frac{A}{r} e^{-r} + \frac{B}{r} e^{r}. \]  

(3.6)

To determine the amplitudes of the wave function given in Equation (3.6) the boundary conditions must be applied. First, as the electron moves out to infinity the wave function must be finite which implies \( B = 0 \). The second condition is the probability of finding the electron in the system bounded by the surface area is unity[21], implying

\[ \int_0^\infty dr 4\pi r^2 |R(r)|^2 = 1. \]

Integration of the previous equation produces

\[ A = \sqrt{\frac{\eta_1}{2\pi}}. \]
Therefore, the radial wavefunction for an electron out of the trap is given by

\[ R(r) = \sqrt{\frac{\eta_1}{2\pi}} e^{-\frac{\eta_1 r}{r}}, \quad (3.7) \]

which is equivalent to the expression developed by Roy [22].

To complete the solution of the TISE, the trap well potential strength must be obtained. This is done by multiplying Equation (3.3) by \(4\pi r^2\), due to the limited probability density function, to obtain

\[- \frac{2\pi \hbar^2}{m_1^*} \frac{d}{dr} (r^2 \frac{dR}{dr}) + 4\pi r^2 V_\delta(r) R(r) = -(\phi_B + E_C - E)4\pi r^2 R(r). \quad (3.8)\]

Equation (3.8) can be evaluated by integrating the radius from zero to some finite distance, \(\epsilon\), and taking the limit as \(\epsilon\) approaches zero, to find the strength of the trap potential is:

\[ V_\delta R(0) = \frac{2\pi \hbar^2}{m_1^*} \epsilon^2 \frac{d}{dr} (R(r))|_{\epsilon}. \]

Differentiating Equation (3.7) and taking the limit as \(\epsilon \to 0\) the desired result is obtained

\[ V_\delta R(0) = -\frac{\hbar^2}{m_1^*} \sqrt{2\pi \eta_1}. \quad (3.9) \]

Following a similar procedure for a trap at the interface the radial wavefunction in the oxide \((r > 0)\) and the strength of the trap potential are seen to be, respectively,

\[ R_i(r) = \sqrt{\frac{\eta_2}{2\pi}} e^{-\frac{\eta_2 r}{r}}, \quad (3.10) \]

and

\[ V_\delta R(0) = -\frac{\hbar^2}{m_2^*} \sqrt{2\pi \eta_2}, \quad (3.11) \]

where

\[ \eta_2^2 = \frac{2m_2^*}{\hbar^2} (E_C - E) \quad (3.12) \]

and \(m_2^*\) is the effective mass of an electron in silicon.
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Figure 3.5: The geometry associated with trap-to-trap tunneling is shown. Trap I is located at the interface between the semiconductor and the insulator while trap A is located within the insulator.

3.3 Trap-to-Trap Tunneling Time Constant

The solution to the TISE is obtained in order to develop an interface trap to bulk oxide trap tunneling time constant. By following the method of Bardeen which utilizes the matrix element of tunnel transition and the Golden Rule of transition probability a time constant may be developed[23]. In general, the matrix element is given by

\[ M_{AI} = \int \text{d}^3r \psi_I^*(\hat{H} - E)\psi_A \]

where \( \hat{H} \) is the Hamiltonian and \( E \) is the energy of the system. The indices A and I represent the location of the traps as shown in Figure 3.5.

For the case of a delta function potential the matrix element is simply,

\[ M_{AI} = \int \text{d}r 4\pi r^2 R_I^*(r)V_0 \delta(r)R_A(r), \]
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which upon evaluation gives

\[ M_{AI} = -\frac{\hbar^2}{m_1^*} \sqrt{\gamma_1 \gamma_2} e^{-\gamma r}. \] (3.13)

To obtain the probability of transition from one trap to another the Golden Rule of transition probability is used. The rule states, the transition probability, \( p \), per unit time and space is proportional to the product of the square of the matrix element and the final energy distribution of states, \( \rho(E) \). In equation form the rule is written as

\[ p = \frac{2\pi}{\hbar} |M_{AI}|^2 \rho(E). \]

Squaring Equation (3.13) and substituting into the above equation the transition probability is given by

\[ p = \frac{4\pi^2 \hbar^3 \gamma_1 \gamma_2 D_{it}}{m_1^{*2}} e^{-2\gamma \sqrt{y^2 - y'^2}} \]

where the final energy distribution of states is given by

\[ \rho(E) = 2\pi r' D_{it}. \]

The total transition probability per unit time, \( P \), is obtained by integrating, over all space, the spatially distributed transition probability;

\[ P = \frac{4\pi^2 \hbar^3 \gamma_1 \gamma_2 D_{it}}{m_1^{*2}} \int_x^\infty \frac{e^{-2\gamma \sqrt{y^2 - x^2}}}{y^2} r' dr'. \] (3.14)

From the geometry of the system Equation (3.14) can be simplified. In particular note

\[ r' = \sqrt{y^2 - x^2} \]

and

\[ dr' = \frac{y}{\sqrt{y^2 - x^2}} dy. \]

Substitution of these values into Equation (3.14) produces

\[ P = \frac{4\pi^2 \hbar^3 \gamma_1 \gamma_2 D_{it}}{m_1^{*2}} \int_x^\infty \frac{e^{-2\gamma \sqrt{y^2}}}{y} dy. \] (3.15)
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The integral in Equation (3.15) is known to be the exponential integral function:

\[
\int_{x}^{\infty} \frac{e^{-u}}{u} \, du = -Ei(-x),
\]

which can be integrated by parts twice to obtain a series solution which converges for large enough \( x \), such that,

\[
\int_{x}^{\infty} \frac{e^{-u}}{u} \, du = e^{-x/(1 + \frac{1}{x^2} + \ldots)}.
\]

For the problem at hand let \( u = 2\eta_1 y \) and \( du = 2\eta_1 dy \) or \( y = u/2\eta_1 \) and \( dy = du/2\eta_1 \). Substitution of the aforementioned change of variables into Equation (3.15) produces

\[
P = \frac{4\pi^2 h^3 \eta_1 \eta_2 D_{it}}{m_1^* \gamma} \int_{2\eta_1 x}^{\infty} \frac{e^{-u}}{u} \, du.
\]

Recognizing the first two terms of the series solution of the exponential integral function as the first two terms of a binomial expansion, the total transition probability per unit time can be written as

\[
P = \frac{2\pi^2 h^3 \gamma_2 D_{it}}{m_1^* \gamma_x} e^{-2\eta_1 x}.
\]  

(3.16)

The final step to obtaining an expression for the trap-to-trap tunneling time constant is simply to invert Equation (3.16). Thus, the trap-to-trap tunneling time constant is given by

\[
\tau(E_t, x) \equiv \frac{1}{P} = \frac{m_1^* \gamma_x (1 + \frac{1}{2\eta_1 x})}{2\pi^2 h^3 \gamma_2 D_{it}} e^{2\eta_1 x}.
\]  

(3.17)

As indicated in this equation the trap-to-trap tunneling time constant is inversely proportional to the density of interface traps. Thus, an increase in \( D_{it} \) causes the tunneling process to be enhanced which is an expected result since the tunneling current (probability) is proportional to the final density of states.

It is interesting to note at \( x = 0 \) there is still a finite probability of tunneling and hence a tunneling time constant

\[
\tau(0) = \frac{m_1^* \gamma_x}{4\pi^2 h^3 \gamma_2 D_{it}}.
\]
CHAPTER 3. TUNNELING

Substituting Equations (3.4) and (3.12) and assuming \( m_1^* = m_2^* = m \) this time constant is given by

\[
\tau(0) \approx \frac{m}{4\pi \hbar \sqrt{E_C(\phi_B + E_C)D_u}}.
\]

The uncertainty of the definition of the interface may account for the observed \( \tau(0) \). From the Heisenberg uncertainty principle the uncertainty between time and energy is greater than Planck's constant, i.e.

\[
\Delta t \Delta E \geq \hbar.
\]

With \( \Delta t \sim \tau(0) \) and \( \Delta E \sim \sqrt{E_C(\phi_B + E_C)} \) the Heisenberg uncertainty principle is satisfied,

\[
\Delta t \Delta E = \frac{m}{4\pi \hbar D_u} \sim 10^{-33} \geq \hbar.
\]
Chapter 4
Experimental

In the previous chapters the theory of charge pumping and the theory of tunneling were introduced. A theoretical understanding of any problem is important, however, of equal importance is the experimental results which support and reinforce the theoretical understanding. Thus, this chapter will first discuss the experimental setup followed by a discussion of the experimental results.

4.1 Experimental Setup

A simplified version of the experimental setup is shown in Figure 2.1, where a periodic square waveform is applied to the device under test (DUT) and the resultant current is measured through the source and drain. A block diagram of the actual experimental setup is shown in Figure 4.1. The charge pumping measurement has been fully automated and is controlled by an HP9000 model 310 computer. The periodic square waveform is supplied by an HP8115A programmable pulse generator and the resultant charge pumping current is measured by a Keithley 616 electrometer. Once the analog current has been measured it is converted to a digital equivalent which may be collected and stored by the computer. The A/D conversion is provided by an HP59313A A/D converter. A bulk bias may be applied to the DUT via an in-house constructed battery box.

Due to the large amounts of data which are collected and interpreted during
Figure 4.1: A block diagram of the automated charge pumping experimental setup. The HP8115A programmable pulse generator applies a periodic square waveform to the device under test. The resulting charge pumping current is measured via a Keithley 616 electrometer and A/D converted with an HP59313A. Bulk bias is applied to the DUT via a battery box. Automated control is provided with an HP9000 model 310.
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charge pumping, automated data acquisition is a must. Control of the charge pumping measurement is provided by the menu-driven software program FIDDLER version 18.\(^1\) When FIDDLER18 is initiated, the user is presented a menu of options which are accessed via soft-keys. All measurement techniques are accessible when the Measurements soft-key is chosen.

Charge pumping is one of the measurements which may be performed simply by choosing the Charge Pumping soft-key. When the charge pumping menu is invoked, the user is presented with ten soft-key options which are described below:

- **SK1 (Quit/Store):** Pressing SK1 allows the user to leave the charge pumping routine and return to the Measurements routine. Shift-SKI is pressed when data is to be stored to (or loaded from) floppy disk.

- **SK2 (Pars/4145):** Pressing SK2 allows the user to view and establish the parameters of the selected charge pumping test. When Shift-SK2 is pressed the HP4145 Semiconductor Parameter Analyzer is accessed, allowing I-V and gated diode measurements to be made.

- **SK3 (Print Pars/User):** The parameters may be printed to a printer connected to the bus by pressing SK3. Typically, a plot of the collected data and the parameters are printed on one page creating a hard copy of the measurement conditions and the results. Pressing Shift-SK3 sends the operator to a data analysis routine.

- **SK4 (Select Test):** Various charge pumping tests are selected by this key. There are currently five tests which may be selected.

  1. **Vary Base Level:** Bi-level charge pumping varying the base level as described in Chapter 2 is performed by selecting this test. Once the

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\(^1\)The Friendly Interactive Data Dowser for Learned Extractors by Richard (FIDDLER) program was written by Richard Booth. The idea for FIDDLER was to bring together all the measurement and analysis routines into one integrated software package and to adopt a standard for data storage on floppy disk eliminating the multitude of incompatible data sets among the individuals in the Sherman Fairchild Center. New students are encouraged to use FIDDLER and to add new routines applicable to their own research.
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test is selected the user is automatically entered into the parameter modification routine. The user may modify the initial base level voltage, the ending base level voltage, the amplitude of the pulse, the number of data points to measure, the frequency of the pulse, and the rise and fall times of the pulse.

2. **Vary Frequency:** A sweep of the frequency of the applied waveform may be obtained by choosing this test. The base voltage level is fixed at the level which produces the maximum charge pumping current and the frequency is subsequently varied. The user may modify the number of data points to measure, the initial frequency, the ending frequency, the wave type (square or triangular), the sampling type (logarithmic or linear), and the sweep direction (low-to-high or high-to-low). A plot of the charge pumping current, or charge recombined per cycle, may be obtained.

3. **Vary Rise and Fall Time:** The geometric mean of the capture cross-sections may be obtained by varying the rise and fall times of the applied pulse. Similar to the vary frequency test, the base level is fixed at the voltage which produces the maximum charge pumping current. The frequency and number of data points to measure may be modified. The program automatically calculates the rise and fall times from the frequency and the resolution of the pulse generator.

4. **Tri-Level:** Tri-level charge pumping is performed with this selection. A third voltage level is introduced in the tri-level measurement such that individual trap energies may be probed. The user may modify the rise time, the fall time to the step level, the fall time from the step level, the period of the signal (the period may be allowed to vary), the starting step level time duration, the ending step level time duration, the voltages beyond flatband and threshold, the number of data points, a leading edge or trailing edge step, the step
voltage level, and the inversion-accumulation time (if a variable period is chosen). The threshold and flatband levels may be entered automatically by performing the vary base level test prior to execution or by entering the values manually using the Test Pars soft-key.

5. Vary Amplitude: For a specified frequency the amplitude of the applied waveform is varied. The user may select the starting amplitude, the ending amplitude, and the base level. All other parameters, such as frequency and rise and fall times, are modified by selecting the vary base level test.

- SK5 (Start): Execution and data acquisition of the selected test is initiated by pressing this key.

- SK6 (Extract Pars): Upon the completion of the test the user may choose to extract information from the measurement. The width and length of the DUT is entered and an automatic printout of the desired results is obtained.

- SK7 (Plot): After a measurement is complete the data may be plotted by pressing this key. Once the plot routines are invoked the various plotting parameters may be changed to customize the plot. A data editor is also available for performing basic data manipulations. A hard copy of the plot may be obtained by dumping the plot screen to the printer.

- SK8 (Auto Mode): For the tri-level measurement, a complete set of data may take several hours to acquire. When auto mode is selected the voltage step level is swept and the data is stored, automatically, on disk for future analysis.

- SK9 (Setup Insts): The parameters affecting the instruments and the program in preparation for a measurement, are set with this key. These parameters include, the sensitivity and range of the electrometer, the sensitivity and channel of the A/D converter, the settling time for the measurement, which
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instrument will measure the current, manual or automatic control, any bias voltage instrument connected, and the temperature.

• SK10 (Test Pars): The threshold and flatband voltages of a particular device may be entered in this routine. If these voltages are not entered they will be automatically extracted from vary base level data.

The experimental setup is very flexible in the number of devices which may be examined since devices at the wafer level as well as packaged devices may be tested. A shielded probe stand was constructed, in-house, to provide relatively simple testing of devices at the wafer level. By looking through a microscope the probe tips are gently placed on the appropriate bonding pad for measurement. The probes are interfaced to the electrometer via triaxial or coaxial cables. The probe stand is connected to a vacuum pump to hold the wafer down to the chuck. To reduce the moisture which may accumulate on the wafer nitrogen may be blown into the probe stand.

If the devices have been bonded into low-leakage packages then they may be tested by insertion into a shielded integrated circuit (IC) test box. The IC test box was constructed in-house with both triaxial and coaxial connectors. Dry nitrogen may be blown over the wafer inside the box to reduce the effects of the humidity. The packaged devices may be measured from room to cryogenic temperatures. All low temperature measurements are performed in an in-house constructed cryostat[24].

Due to the relatively low current levels which are being measured, precautions must be taken to reduce the noise. The shielding of the probe stand and IC test box reduces the noise induced by electromagnetic fields. The probe stand has been isolated from vibrations and care is taken so as not to bump the stand during the measurement in an attempt to reduce anomalous readings. Triaxial and coaxial cables are used to reduce the leakage currents and noise further. Thus, extreme care must be taken in testing devices.
CHAPTER 4. EXPERIMENTAL

4.2 Experimental Results

The expression for the tunneling time constant, Equation (3.17), is seen to be a function of the tunneling distance and dependent essentially on two parameters, the density of interface traps and the trap energy. Figure 4.2 plots Equation (3.17) as a function of tunneling distance with the density of interface traps as a parameter. The trap energy is assumed to be 0.1eV below the conduction band. Similarly, Equation (3.17) can be plotted as a function of the tunneling distance with trap energy as a parameter, as shown in Figure 4.3.

Ellipsometry measurements made on control wafers revealed the tunnel oxide thickness of the ultra-thin SONOS device to be 12Å. From Equation (3.17) the tunneling distance can be verified. Measurements of the average density of interface traps, by charge pumping at high frequencies, and the tunneling time constant \( \tau = 1/f_{\text{break}} \) yielded values of \( 4 \times 10^{11} \text{cm}^{-2} \text{eV}^{-1} \) and \( 10^{-5} \text{sec} \), respectively. The 'breakpoint' frequency, \( f_{\text{break}} \), is determined to be the frequency where the \( Q_{\text{cp}} \) versus \( f \) curve deviates from the classically predicted constant line. With these experimentally determined values and Figure 4.2 the tunneling distance is shown to be approximately 12Å, which lends support to the proposed trap-to-trap model.

Conventional SONOS devices with a 20Å tunnel oxide and a \( D_s \) measured to be \( 7 \times 10^{10} \text{cm}^{-2} \text{eV}^{-1} \) would be expected to have a break frequency of approximately 1Hz; however, this could not be observed due to limitations with the instrumentation. For the positively biased MOS irradiated sample the interface density and tunneling time constant were measured to be \( 1 \times 10^{11} \text{cm}^{-2} \text{eV}^{-1} \) and \( 10^{-2} \text{sec} \), respectively, corresponding to a tunneling distance of 17Å.

The calculation of the tunneling distance via Figure 4.2, assumes a trap energy 0.1eV below the conduction band. As seen in Figure 4.3, the energy of the near-interface oxide trap is not critical since the time constant has a relatively low dependence on the trap energy for the tunneling distances examined.
Figure 4.2: Equation (3.17) plotted for various values of interface state density. As the interface density increases, the time constant for the trap decreases. From the breakpoint in the $Q_{cp}$ versus $f$ curve, a time constant is calculated, and from this figure the distance the bulk dielectric trap is located from the interface may be inferred. In this figure, $E_C - E_t = 0.1\text{eV}$. 
Figure 4.3: Equation (3.17) plotted for various values of bulk dielectric trapping levels. Compared with the interface state density dependence this plot shows slight energy level dependence, especially for traps located within 15Å of the interface.
Chapter 5

Conclusions and Recommendations

5.1 Conclusions

Charge pumping experiments performed on $^{60}$Co irradiated oxide devices show an additional current component which is attributed to charging and discharging of bulk oxide traps located spatially near the Si-SiO$_2$ interface. The additional current produces an increase in the charge recombined per cycle at lower frequencies contradicting the present theory which predicts the charge to be independent of frequency. Close correlation between the frequency at which the charge recombined deviates from classical theory and the theoretical trap-to-trap tunneling time constant supports a trap-to-trap tunneling mechanism as a plausible explanation. SONOS devices fabricated with a nitride trapping layer intentionally placed 12Å from the interface exhibited a frequency dependence of the charge recombined per cycle similar to the irradiated devices. Confirmation of the distance from the interface to the trapping layer lends further support to the proposed mechanism.

5.2 Recommendations

The near-interface trapping states may pose a reliability problem to high precision analog circuits. Although the near-interface traps were intentionally created for this study, latent defects in the dielectrics of devices operated within a circuit
can produce additional noise as well as errors in circuit performance due to charge storage and release effects. These effects may be considerable in switched capacitor filters, charge coupled devices, charge redistribution analog-to-digital converters, and sample-and-hold circuits.

Since near-interface oxide traps pose a reliability problem further study is needed. The variable frequency technique of charge pumping presented in this thesis is a definitive experimental method for differentiating near-interface oxide traps from interface traps. At low frequencies the near-interface oxide trap contribution may be investigated, while at the high frequencies the interface trap component may be examined.

Certain processing steps, such as plasma etching, reactive ion etching, and RF sputtering, create an abundance of interface and near-interface oxide traps. If there is no subsequent anneal, typically in a 'forming' gas (N₂H₂) ambient, the devices will not operate effectively. The anneal tends to remove these defects, however, it is not well known how the defects are passivated. Utilizing variable frequency charge pumping the annealing process may be studied by separating the passivation of interface traps from the passivation of near-interface traps. Thus, a new benchmark for the density of near-interface oxide traps may be established providing higher standards of reliability.

Incorporation of near-interface oxide traps into the charge pumping model is currently being investigated. Following the work of Tewksbury[9] a pair of coupled differential equations have been developed which govern the emission from near-interface and interface traps. The coupled equations are shown in Equations (5.1) and (5.2):

\[
\frac{\partial}{\partial t} \rho_{at}(E_t, x, t) = - \frac{\rho_{at}(E_t, x, t)}{\tau(E_t, x)} + \frac{\rho_{at}(E_t, x)}{\tau(E_t, x)} D_{at}(E_t, t) \tag{5.1}
\]

and

\[
\frac{\partial D_{at}(E_t, t)}{\partial t} = -e_n(E_t)D_{at}(E_t, t) - \frac{\partial}{\partial t} \int_{0}^{t_{ox}} \partial x \rho_{at}(E_t, x, t) \tag{5.2}
\]

where \( \rho_{at}(E_t, x, t) \) is the density of occupied oxide traps, \( \rho_{at}(E_t, x) \) is the total density of oxide traps, \( t_{ox} \) is the thickness of the dielectric, and \( \tau(E_t, x) \) is the trap-to-trap
CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

tunneling time constant given by Equation (3.17). These differential equations may be uncoupled if the rise and fall times are kept much less than the period of the applied charge pumping waveform. Since the equations are decoupled the total charge pumping current,

\[ I_{cp} = I_{cpit} + I_{cpot}, \]

is the sum of an interface trap current component, \( I_{cpit} \), and a near-interface trap current component, \( I_{cpot} \). Solving the decoupled differential equations will produce a new quantum mechanical charge pumping model.

Also in progress is the development of a low noise electrometer to remove the limitations of instrumentation currently restricting the application of very low frequency charge pumping measurements. In order to determine the energy distribution of the near-interface traps tri-level charge pumping measurements are being investigated.

Variable frequency charge pumping may be utilized extensively in device physics studies. It has already been shown to be useful in examining the effects of ionizing radiation, but it also may be readily applied to hot electron injection studies. However, the technique is not limited to the device physics area. In a manufacturing process variable frequency charge pumping may be performed to estimate the reliability of a device to be marketed. The future of variable frequency charge pumping is indeed a bright one.
References


REFERENCES


REFERENCES


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Appendix A

Fabrication Sequence

The MOS devices used in this study were fabricated by Dr. R.R. Siergiej following an abbreviated NMOS fabrication sequence[26, 27]. The ultra-thin tunnel oxide SONOS devices were fabricated by M.L. French following a process sequence which omitted the tunnel oxidation step[28].

A.1 The NMOS Processing Sequence

Positive fixed oxide charge induced by radiation tends to invert lightly doped p-substrates. Therefore, heavily doped p-substrate material (0.1-0.2 Ω·cm) was used. This process sequence is summarized below.

1. Starting material: p-< 100 > 0.1-0.2 Ω·cm
   - Number device wafers
   - Number control wafers

2. Field Oxide, Active Device Regions: \( t_{ox}=5\text{kÅ} \)
   - RCA clean
   - High temperature oxidation. 5kÅ oxide: 1100°C, 50min
   - Phtolithography: \( p^+ \) mask
   - Buffered HF etch: 5kÅ oxide
   - Strip photoresist: PRS-2000
APPENDIX A. FABRICATION SEQUENCE

3. Gate Electrode: ONO prepared in Triple Wall Oxide (TWO) system[29]
   - RCA clean
   - Flourinate: (optional) 1% HF, 5min
   - High temperature TWO oxidation: POA in Argon ambient, 900°C, 15min
   - LPCVD Nitride: 735°C, 250mTorr, 20sccm SiH₂Cl₂, 100sccm NH₃
   - High temperature reoxidation of Nitride: 1000°C, steam, 50min
   - LPCVD Polysilicon: 5kÅ, 625°C, 30min, 800mTorr, SiH₄ 20% and N₂ 80% mix, 180sccm
   - Photolithography: polysilicon mask
   - Plasma Etch: 5kÅ polysilicon; 250 Watts, 265mTorr, 100sccm SF₆
   - Etch: Oxide, Buffered HF; Nitride, Hot phosphoric acid
   - Strip photoresist: PRS-2000

4. n⁺ Diffusion
   - RCA clean
   - High temperature diffusion: POCl₃, 900°C, 20min
   - Diffusion drive-in: Nitrogen anneal; 900°C, 30min
   - Strip P₂O₅ glass and pad oxide: Buffered HF etch

5. Contact Windows
   - RCA clean
   - High temperature wet oxidation: 1kÅ, 900°C, 18min
   - Photolithography: Contact window mask
   - Etch oxide: Buffered HF etch
   - Strip photoresist: PRS-2000
APPENDIX A. FABRICATION SEQUENCE

6. Metallization
   - Etch oxide: 1% HF solution
   - Metallization: 7kÅ Aluminum, sputtered
   - Photolithography: Metallization mask
   - Etch: 7kÅ Aluminum, PAN etch, 45°C, 2min
   - Strip photoresist: PRS-2000

7. Backside Metallization
   - Spin photoresist on the front side
   - Plasma etch: Backside, 300 Watts, 300mTorr, 100sccm SF$_6$
   - Etch oxide: Buffered HF etch solution (backside)
   - Metallization: 7kÅ Aluminum, evaporated
   - Strip photoresist: PRS-2000

8. Post Metal Anneal
   - Organic clean: 10min Acetone, 10min Methanol
   - Nitrogen/Hydrogen Anneal: 350°C, 30min

A.2 The SONOS Fabrication Sequence

The standard SONOS processing sequence is listed below. For the fabrication of ultra-thin tunneling oxide devices, the tunnel oxidation step is omitted. The ultra-thin oxide was grown during the fifteen minute warm-up period prior to the nitride deposition.

1. Starting Material: p-<100> 2-3 Ω-cm
APPENDIX A. FABRICATION SEQUENCE

- Number device wafers
- Number control wafers

2. LOCOS Oxidation

- RCA clean
- Pad oxidation (wet): 950°C, 12min, 300Å
- LPCVD nitride: 750°C, 0.3Torr, NH₃:SiCl₂H₂ = 100:20, 35min, 1200Å
- Photolithography: p⁺ mask
- Plasma etch nitride: 0.3Torr, 125 Watts, CF₄, 2min

3. Field Implant

- Front implant: BF₂, 145keV, 5×10¹⁴cm⁻²
- Back implant: B, 32keV, 2×10¹⁵cm⁻²
- Strip photoresist: PRS-2000
- Anneal: Nitrogen ambient, 950°C, 30min
- Etch oxide: Buffered HF, 1min

4. Field Oxide

- RCA clean
- Wet oxidation: 6kÅ, 1100°C, 70min
- Etch oxide: Buffered HF, 2min
- Etch nitride: H₃PO₄, 165°C, 1hour
- Etch oxide: Buffered HF until hydrophobic

5. Gate Dielectric

- RCA clean
APPENDIX A. FABRICATION SEQUENCE

- Tunnel oxidation (TWO): 700°C, 1.5 l/min O₂, *in situ* Argon anneal 1.5 l/min
- LPCVD nitride: 750°C, 0.3Torr, NH₃:SiCl₂H₂ = 100:33
- LPCVD oxide: 750°C, 0.8Torr, N₂O:SiCl₂H₂ = 100:20
- Anneal (densification): 900°C, 30min, wet oxide

6. Polysilicon

- RCA clean
- LPCVD: 625°C, 0.8Torr, 280sccm SiH₄, 30min, 5kÅ
- Photolithography: Polysilicon mask, (PY1)
- Plasma etch: 5kÅ polysilicon, 0.3Torr, 200Watts, SF₆, 5min, (front and back)
- Etch: chemical ONO structure
- Strip photoresist: PRS-2000

7. n⁺ Diffusion

- RCA clean
- High temperature diffusion: 900°C, POCl₃, 20min
- Diffusion drive in: N₂ ambient, 900°C, 30min
- Etch: p-glass, Buffered HF etch, 15sec

8. Contact Window

- RCA clean
- High temperature wet oxidation: 900°C, 45min, 1200Å
- Photolithography: contact window mask (CW)
- Etch oxide: Buffered HF etch, 4min
APPENDIX A. FABRICATION SEQUENCE

9. Metallization

- RCA clean with HF dip
- Metallization: Aluminum sputtering, 7kÅ, 7Hg, 0.4A
- Photolithography: Metal mask (MET)
- Etch Aluminum: PAN etch, 45°C, 2min
- Strip photoresist: PRS-2000

10. Backside Metallization

- Spin photo resist on front side
- Etch oxide: Buffered HF until hydrophobic
- Metallization: Aluminum sputtering, 7kÅ, 7Hg, 0.4A
- Strip photoresist: PRS-2000

11. Post Metal Anneal

- Organic clean: 10min Acetone, 10min Methanol
- Anneal: Hydrogen/Nitrogen ambient, 475°C, 30min
Appendix B

Solution to Equation (2.10)

The time rate of change of the non-steady state quasi Fermi level is given in Equation (2.12) as:

\[
\frac{dE_m(t)}{dt} = -\frac{kT}{\tau_0} \left(e^{(E_m(t) - E_i)/kT} - e^{(E_i - E_i)/kT}\right).
\]

To solve this differential equation start by separating the equation into the form:

\[
\frac{dE_m(t)}{e^{E_m(t)/kT} - e^{E_i/kT}} = -\frac{kT}{\tau_0} e^{-E_i/kT} dt.
\]  \hspace{1cm} (B.1)

The right half of Equation (B.1) is solved simply by integrating:

\[
\frac{kT}{\tau_0} \int_0^t e^{-E_i/kT} dt.
\]

The left half of Equation (B.1) is more complex. Looking into the integral tables this integral resembles the form

\[
\int \frac{dx}{a + be^{px}} = \frac{x}{a} - \frac{1}{ap} \ln (a + be^{px})
\]

where

\[
a = -e^{E_i/kT},
\]

\[b = 1, \quad p = 1/kT, \quad \text{and} \quad x = E_m(t).\]  Making this substitution the integral is solved to become:

\[
\int_{E_m(0)}^{E_m(t)} \frac{dE_m(t)}{e^{E_m(t)/kT} - e^{E_i/kT}} = -E_m(t)e^{-E_i/kT} + kT e^{-E_i/kT} \ln \left[ e^{E_m(t)/kT} - e^{E_i/kT} \right]_{E_m(0)}^{E_m(t)}
\]

\[= e^{-E_i/kT}(E_m(0) - E_m(t)) + kT \ln \left[ \frac{e^{E_m(t)/kT} - e^{E_i/kT}}{e^{E_m(0)/kT} - e^{E_i/kT}} \right].
\]
APPENDIX B. SOLUTION TO EQUATION (2.10)

Equating the two halves to obtain the solution yields:

\[-kT \frac{kT}{\tau_0} e^{-E_i/kT} = e^{-E_i/kT} \left( kT \ln \left[ \frac{e^{E_m(t)/kT} - e^{E_i/kT}}{e^{E_m(0)/kT}} \right] - [E_m(t) - E_m(0)] \right)\]

which can be simplified to

\[-\frac{t}{\tau_0} e^{(E_i - E_m(t))/kT} = \ln \left[ \frac{1 - e^{(E_i - E_m(t))/kT}}{1 - e^{(E_i - E_m(0))/kT}} \right].\]

Raising each side as a power of the exponential the following results:

\[\exp \left[ -\frac{t}{\tau_0} e^{(E_i - E_m(t))/kT} \right] = \frac{1 - e^{(E_i - E_m(t))/kT}}{1 - e^{(E_i - E_m(0))/kT}}.\]

Collecting the \(E_m(t)\) term onto the left side of the equation:

\[e^{(E_i - E_m(t))/kT} = 1 - \left[ 1 - e^{(E_i - E_m(0))/kT} \right] \exp \left[ -\frac{t}{\tau_0} e^{(E_i - E_i)/kT} \right].\]

Taking the natural logarithm of each side results in the desired solution, Equation (2.13):

\[E_m(t) = E_1 - kT \ln (1 - (1 - e^{(E_i - E_m(0))/kT}) e^{-\frac{t}{\tau_0} e^{(E_i - E_i)/kT}}).\]
Appendix C

Angular Solution to Schröedinger's Equation

The angular portion of Schröedinger's equation may be written as:

\[
\frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial Y(\theta, \phi)}{\partial \theta} \right) + \frac{1}{\sin^2 \theta} \frac{\partial^2 Y(\theta, \phi)}{\partial \phi^2} = -\lambda Y(\theta, \phi), \tag{C.1}
\]

or in the form of the angular momentum operator, \( \hat{L}^2 \),

\[
\hat{L}^2 Y(\theta, \phi) = \hbar^2 \lambda Y(\theta, \phi)
\]

where

\[
\hat{L}^2 = -\hbar^2 \left[ \frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial}{\partial \theta} \right) + \frac{1}{\sin^2 \theta} \frac{\partial^2}{\partial \phi^2} \right].
\]

If the separation of variables technique is applied to Equation (C.1) by assuming a solution of the form:

\[Y(\theta, \phi) = \Theta(\theta)\Phi(\phi),\]

then a separated equation is obtained:

\[
\frac{\sin \theta}{\Theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial \Theta}{\partial \theta} \right) + \lambda \sin^2 \theta + \frac{1}{\Phi} \frac{\partial^2 \Phi}{\partial \phi^2} = 0. \tag{C.2}
\]

In order to obtain a solution the \( \phi \) portion of Equation (C.2) is forced to oscillate such that

\[
\frac{1}{\Phi} \frac{\partial^2 \Phi}{\partial \phi^2} = -m^2
\]

or

\[
\frac{\partial^2 \Phi}{\partial \phi^2} + m^2 \Phi = 0. \tag{C.3}
\]
APPENDIX C. ANGULAR SOLUTION TO SCHRÖEDINGER'S EQUATION

The solution of Equation (C.3) is

\[
\Phi(\phi) = \begin{cases} 
Ae^{im\phi} + Be^{-im\phi} & \text{for } m \neq 0 \\
C + D\phi & \text{for } m = 0
\end{cases}
\]

which must also satisfy the eigenvalue condition:

\[
\frac{\hbar}{i} \frac{\partial \Phi}{\partial \phi} = \hbar m \Phi,
\]

which comes about from realizing all useful solutions must be eigenfunctions of \(\hat{L}^2\) and the \(z\)-component of the angular momentum vector operator, \(\hat{L}_z\). The eigenvalue condition is only satisfied if \(B = 0\), thus,

\[
\Phi = Ae^{im\phi}. \tag{C.4}
\]

The \(\theta\) dependent term of Equation (C.2) may now be solved by setting it equal to \(m^2\) to obtain:

\[
\frac{1}{\sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial \Theta}{\partial \theta} \right) + \left( \lambda - \frac{m^2}{\sin^2 \theta} \right) \Theta = 0. \tag{C.5}
\]

Setting the eigenvalue \(\lambda = l(l + 1)\), Equation (C.5) is seen to be in the form of the associated Legendre differential equation with solutions of the form of the associated Legendre functions:

\[
P_l^m(\cos \theta) = (\sin^2 \theta)^{m/2} \frac{d^2}{d \cos \theta^m} P_l(\cos \theta) = \Theta(\theta). \tag{C.6}
\]

Multiplying Equations (C.4) and (C.6)

\[
\Theta(\theta) \Phi(\phi) = Ae^{im\phi} P_l^m(\cos \theta) = Y_l^m(\theta, \phi)
\]

results in the spherical harmonics, where the eigenvalue equation is:

\[
\hat{L}^2 Y_l^m = \hbar^2 l(l + 1) Y_l^m.
\]
Vitae

Ronald Eugene Paulsen was born March 6, 1968 in Hampton, Iowa to Richard and Sharon Paulsen. He attended the University of Iowa from August 1986 to August 1991 graduating with a Bachelor of Science degree in Electrical Engineering. From September 1987 to August 1990 he worked at the Naval Research Laboratory (NRL), Washington, D.C., on a Cooperative Education program assignment. Since August 1991 he has been enrolled as a full time graduate student at Lehigh University.

Since arriving at Lehigh he has gained experience both in teaching and research. During the academic year 1991-1992 he served as a teaching assistant for microelectronic circuit design classes, while conducting research under a contract supported by NRL. His research interests include interface and near-interface characterization of MOSFETs, irradiation effects of Si and SOI devices, quantum mechanical effects on device modeling, low temperature device physics, device reliability and fabrication issues, and electro-optics.

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