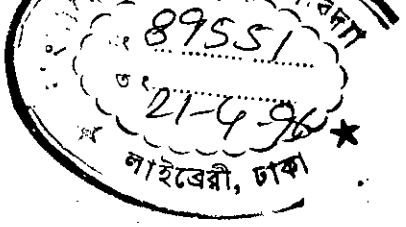
RELAXATION CHARACTERISTICS OF OXIDE TRAPPED CHARGE IN AN MOS STRUCTURE - A QUANTUM MECHANICAL APPROACH

by

Mohammad Nasir Uddin



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CONTENTS

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DEDICATION

DEDICATED TO MY PARENTS

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ABSTRACT

The general MOS structure, it's operation, the oxide trap creation and the effects of interface traps and oxide trapped charge on the ideal MOS characteristics are discussed. In this work, the tunneling of electrons between the conduction band of a semiconductor (or metal) and a trap center in the insulator for an MOS structure is studied. The present analysis use the quantum mechanical wave impedance concept in solving the one dimensional time independent Schrodinger wave equation.

The general physics of coherent resonant tunneling is discussed. A simple analytical model is developed to calculate the life time of oxide trapped charge using stationary state wave function. This model is developed under no applied electric field. This analytical model is developed considering the tunneling probability of trapped charge through both the metal-oxide and semiconductor-oxide interface. The results shows reasonable agreement with other reported results.

A simple analytical formulation is also developed to calculate the effective life time of oxide trapped charge in an MOS structure under different gate voltages and at different time intervals after switching.

ABBREVIATIONS

MOS	Metal-oxide-semiconductor
MOSFET	Metal-oxide-semiconductor field effect transistor
DBRTS	Double-barrier resonant tunneling structure
RT	Resonant tunneling
QMTC	Quantum mechanical transmission coefficient
QMWI	Quantum mechanical wave impedance
WKB	Wentzel-Kramers-Brillouin
VLSI	Very large scale integration

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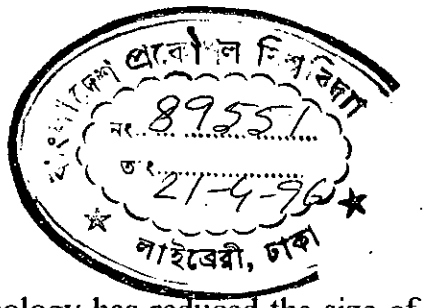
CHAPTER-1

INTRODUCTION



Very Large Scale Integration (VLSI) technology has reduced the size of Metal - Oxide - Semiconductor (MOS) devices to a remarkable extent without reducing the supply voltage. This often causes generation of hot carriers and injection of a fraction of this hot carriers into the insulating films of MOS devices during normal operation. Charge carriers are injected into the oxide if they acquire sufficient energy to overcome the energy barrier during operation under high electric field. While most of the injected carriers are collected at the gate terminal as gate current, a small portion of them are captured by intrinsic trap centers in the insulating (oxide) layer. Charge carriers may also be captured by trap centers created during high field stressing. These trapped charges affect device performance through threshold voltage shift and cause transconductance variation by their involvement in the creation of interface states at the Si / SiO_2 interface [1]. The recovery of the device is very slow after the removal of the external bias. The recovery, however, is accelerated under proper gate bias [2]. Against a good number of experimental reports on charge trapping and subsequent relaxation phenomena in the oxide of MOS structures [3-8], very few reports are available in the literature on theoretical analysis on charge transport through the SiO_2 films [7-9]. Most of the reports describe that relaxation of trapped charge occurs through a tunneling process. However, the charge transport through the insulating films of MOS structures is not clear due to a wide variety of assumptions and nature of treatments among the reports. In this study,

electron transport through thin SiO_2 films of an MOS structure has been discussed elaborately, wherein the trap centers are considered one dimensional delta function and the general formula for life time of trapped electron is obtained from the relationship between position probability density and current density using Green's theorem [10].

1.1 General review :

Experimental investigations on the relaxation of charges trapped in the insulating layer of MOS structures have been carried out extensively during recent years and described 'tunneling discharge' as the most probable mechanism for the relaxation [2,3,8]. Tsu et. al. investigated the resonant tunneling phenomena in heterostructures incorporating multiple quantum wells [11,12]. Theoretical treatment of the resonant tunneling phenomena include Bohm's theory [13] which uses Wentzel- Kramers-Brillouin (WKB) approximation in solving the Schrodinger wave equation and Kane's rigorous analysis [14] which uses the method of wave function matching . Recent treatment is Tsu and Esaki's transfer matrix model [11], which involves the solution of Schrodinger wave equation in each region of the device with the assumptions that the applied bias is small and the effective mass is constant throughout. Later the transfer matrix model is extended to make it directly applicable to arbitrary potential energy profiles. Then Brennan and Summer developed a simple method [15] based on an exact Airy function solution to the Schrodinger wave equation for calculating the transmission probability and current through RT structures. This model is mathematically similar to that of Tsu and Esaki in which a transfer matrix approach is used to couple the incident wave vector to the outgoing wave vector of the resonant tunneling structure.

Ricco and Azbel [16] suggested that the occurrence of resonance involve some complicated physical effects which have so far been overlooked. They showed that

resonant tunneling under the usual experimental conditions implies carrier trapping in the quantum well, hence a build up of space charge available for modifying the potential energy barrier. The tunneling current must then be calculated in a self consistent way, taking into account the contribution due to the trapped electrons. Lundstrom and Svensson derived the analytical formula [9] for life time of oxide trapped charge considering the trap as a 3-dimensional delta function and using the direct tunneling probability for a conduction band electron to the ground state of a trap located at some distance from the interface.

1.2 Overview of the work :

The general physics of resonant tunneling and also the tunneling through the oxide layer of MOS structure is discussed. The calculations are based on the quantum mechanical wave impedance concept developed by Khondker et. al. [17]. The techniques of generating oxide trapped charge is also discussed. An analytical formulation is presented to estimate the life time of oxide trapped charge when the potential stress is withdrawn. It is extended to estimate the effective life time of oxide trapped charge when gate voltage is switched from one to another voltage which is less than the initial applied voltage. The calculation of effective life time for certain delay time after switching is also presented. The effective life time makes use of the distribution of probability density corresponding to the trapped electron due to the initial applied voltage.

The whole analysis have been carried out in n-channel MOS structure. The general formula for life time of oxide trapped charge is obtained by showing similarity with trapped charge carriers for double barrier resonant tunneling (DBRT)structure. At first the life time of oxide trapped charge is formulated without potential stress i.e., the

oxide conduction band is flat. But under external gate bias the oxide conduction band bends linearly. In this case the analytical formula is developed by dividing the total oxide length into pieces so that each small part can be assumed to be flat. Therefore, the techniques discussed above can well be used to estimate the life time of oxide trapped charge at various distance from the interface and the effective life time of oxide trapped charge can also be estimated under applied potential.

CHAPTER-2

GENERAL REVIEW ON MOS STRUCTURE AND OXIDE TRAPPED CHARGE

2.1 Introduction :

MOS diode is the most useful device in the study of semiconductor surfaces. Since the reliability and stability of all semiconductor devices are intimately related to their surface conditions, a understanding of the surface physics with the help of MOS diodes is of great importance to device operation[18]. The MOS has a simple structure and low fabrication cost. For this reason , MOS is very popular device for very large scale integration(VLSI) technology. In this chapter, the basic principle of operation, various oxide charges and the effects of oxide charge on the characteristics of MOS devices are discussed.

2.2 MOS structure :

A MOS transistor is a four terminal device (shown in Fig. 2.1) in which the lateral current flow is controlled by an externally applied vertical electric field. A typical n-channel enhancement type MOS field-effect-transistor (MOSFET) consists of a

relatively lightly doped p type substrate into which two heavily doped n^+ regions are diffused which act as source and drain respectively. The region of inversion layer of mobile electrons between source and drain is the channel and a thin layer of insulating material separates the channel from the metal gate electrode. The metal, oxide and semiconductor channel forms a parallel plate capacitor. The voltage applied to the gate controls the carriers in the conduction channel and thus controls the conductivity of the device.

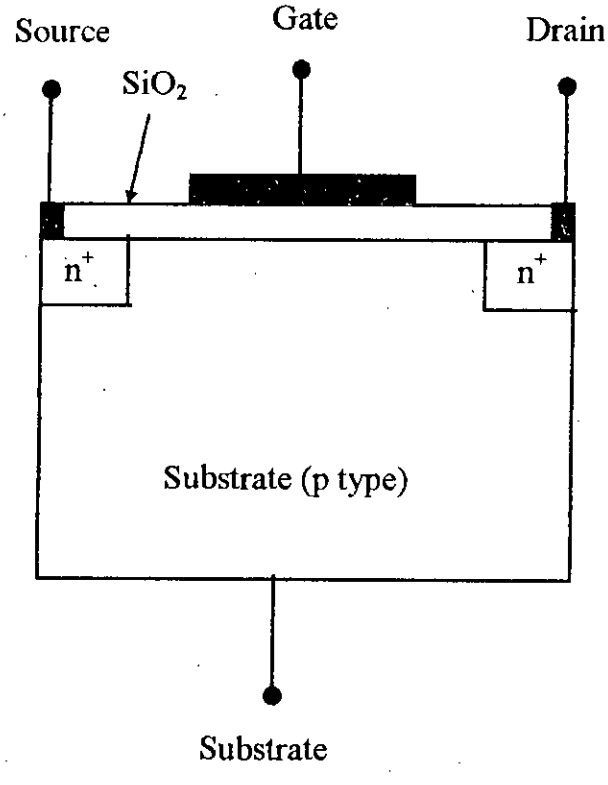


Fig. 2.1 A basic MOS structure.

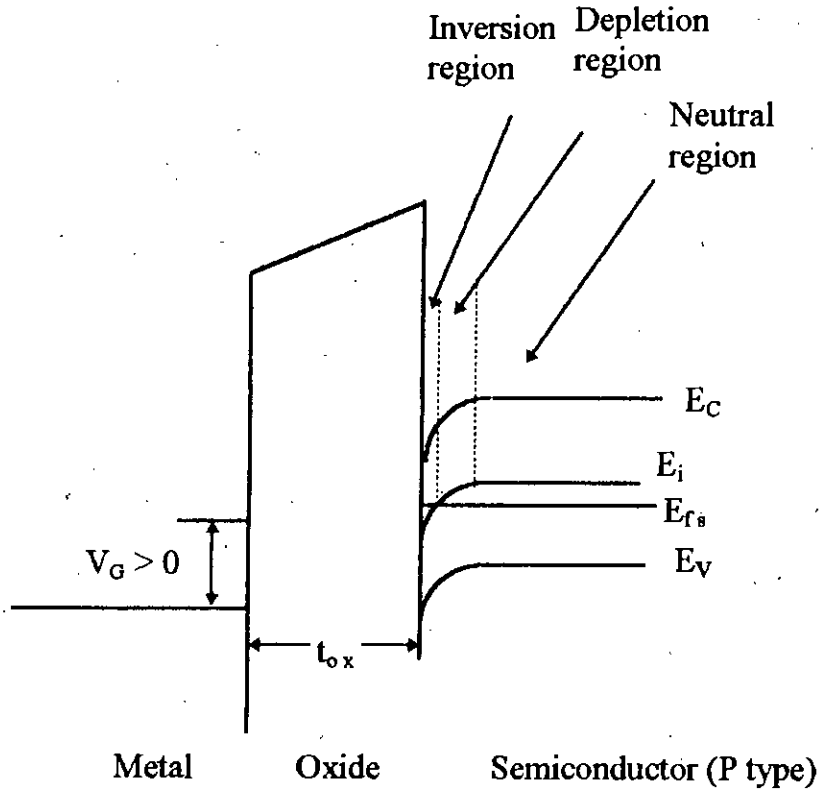


Fig. (a)

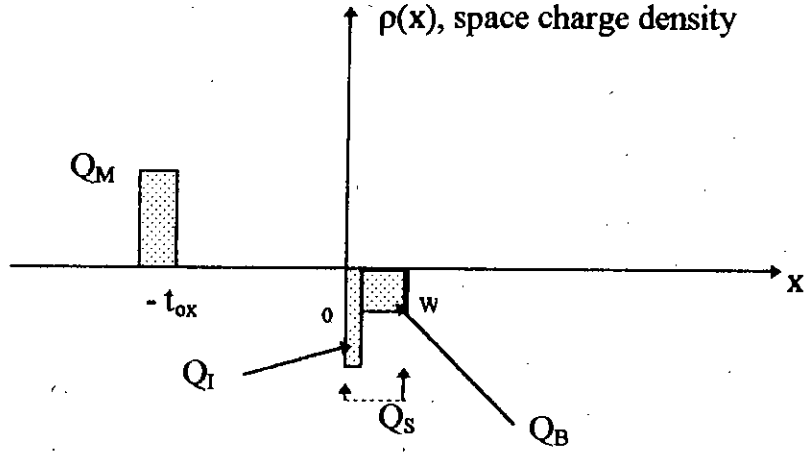


Fig. (b)

Fig. 2.2 (a) Energy band diagram and (b) Charge distribution diagram of an ideal MOS structure.

The threshold voltage V_T of a MOSFET is defined as the minimum voltage which is required to induce the conduction channel [18]. When a gate voltage equal to V_T is applied to a MOSFET it produces a downward bending of the energy band diagram at semiconductor / oxide interface and cause the intrinsic energy level E_i to cross over the constant fermi level by Φ_f at or, near the Si surfaces (Fig. 2.2, 2.3). Then an inversion layer of width w_i is formed at the silicon surface. This region has conduction properties typically of n type material. This region is called the conducting channel of MOS structure. $q\Psi_s$ represents the band bending at the surface and Ψ_s represents the surface potential.

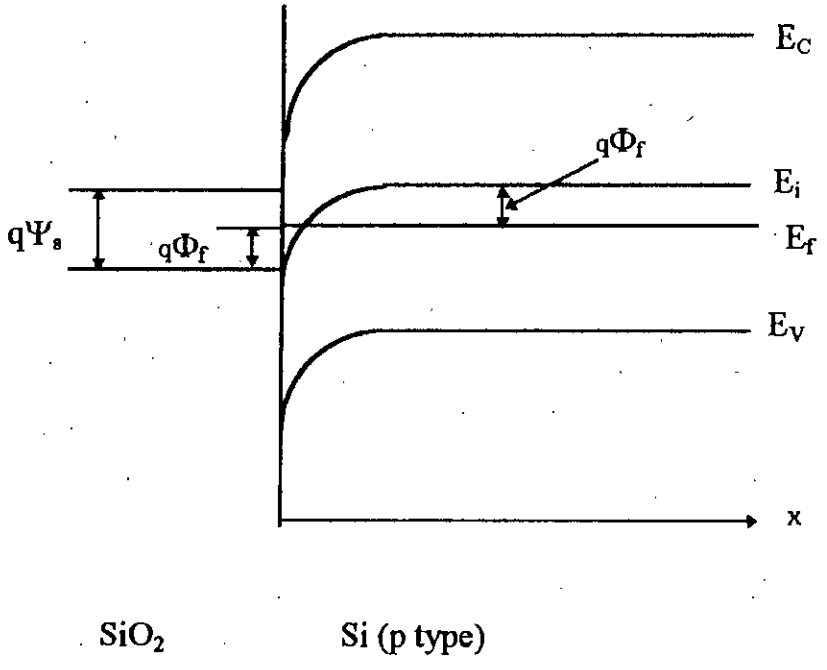


Fig. 2.3 Energy band diagram at the onset of strong inversion

If,

$\Psi_s < 0$, the bands bend up at the surface, hole is accumulated at the surface which happens for (-)ve gate voltage.

$\Psi_s = 0$, flat band condition .

$\Phi_f > \Psi_s > O$, holes are depleted which happens for (+) ve gate voltage.

$\Psi_s > \Phi_f$, we get inversion for more (+)ve gate voltage.

At the on set of strong inversion the surface potential [Fig. 2.3],

$$\Psi_s = 2\Phi_f = \Psi_{si} \qquad (2.1)$$

At the right side of inversion layer a depletion layer of width W (neglecting inversion layer width since it is less than $100A^0$) is produced which extends up to the bulk.

The depletion layer width W and the charges per unit area in depletion layer Q_B is given by

$$W = \sqrt{\frac{2\varepsilon_s \Psi_s}{q N_A}} \qquad (2.2)$$

and,

$$Q_B = -qN_A W \qquad (2.3)$$

Where,

N_A is the doping density of the substrate.

q is the magnitude of electron charge.

The charge balance equation is given by,

$$Q_S = Q_I + Q_B = - Q_M \qquad (2.4)$$

where,

Q_S = total charges per unit area in semiconductor

Q_I = charges per unit area in depletion layer

Q_M = charge per unit area on the metal.

The applied gate voltage is given by,

$$V_G = V_{FB} + \Psi_s + \Psi_o$$
$$= V_{FB} + \Psi_s - Q_S/C_o$$
$$= V_{FB} + \Psi_s + \gamma\sqrt{\psi_s} \quad (2.5)$$

where,

V_{FB} = flat-band voltage

Ψ_s = Surface potential

C_o = Oxide layer capacitance per unit area.

V_{FB} = 0 volt for ideal MOS structure.

$$\gamma = \frac{\sqrt{2q\varepsilon_s N_A}}{C_o} \quad (2.6)$$

$$C_o = \frac{\varepsilon_{ox}}{t_{ox}} \quad (2.7)$$

t_{ox} = oxide thickness.

ε_{ox} = permittivity of oxide layer

ε_s = permittivity of semiconductor

Therefore the threshold voltage can be represented as,

$$V_T = V_{FB} + \psi_s - Q_B/C_o \quad (2.8)$$

Since, at threshold voltage V_T, $Q_S = Q_B$

where,

$\psi_s = 2\Phi_f$ at the on-set of strong inversion.

Again, at the onset of strong inversion $Q_I << Q_B$

$$\text{so, } Q_s = Q_I + Q_B \cong Q_B$$

So, for ideal MOS structure, $V_T = 2\Phi_f - Q_B/C_o$ (2.9)

The flat-band voltage is necessary due to work function difference between the metal and semiconductor and also due to the interface traps and oxide charges.

2.3 Interface traps and oxide charges :

The exact nature of the Si / SiO_2 interface is not yet fully understood. Picture of the interface is that the chemical composition of the interfacial, as a consequence of thermal oxidation is a single crystal silicon followed by a monolayer of SiO_x i.e., incompletely oxidized silicon, then a strained region of SiO_2 and the remained stoichiometric, strain free amorphous, SiO_2 (the compound Si is stoichiometric when x=2 and nonstoichiometric when 2> x >1 [16]. For a practical MOS structure, interface traps and oxide charges exist that will affect the ideal MOS characteristics.

The basic classification of these traps and charges are (Fig.2.4):-

1) interface trapped charge Q_{it} , which are charges located at the Si-SiO_2 interface with energy states in the Si forbidden bandgap and which can exchange charges within a very short time; this charge can possibly be produced by excess silicon (trivalent silicon), excess oxygen, and impurities.

2) fixed oxide charges Q_f, which are located at or, near the interface and are immobile under an applied electric field.

3) oxide trapped charges Q_{ot} , can be created, for example, by x-ray radiation or, hot electron injection ; these traps are distributed inside the oxide layer.

4) mobile ionic charge Q_m, such as sodium ions, which are mobile within the oxide under bias temperature aging conditions. In this thesis, only the oxide trapped charge is discussed.

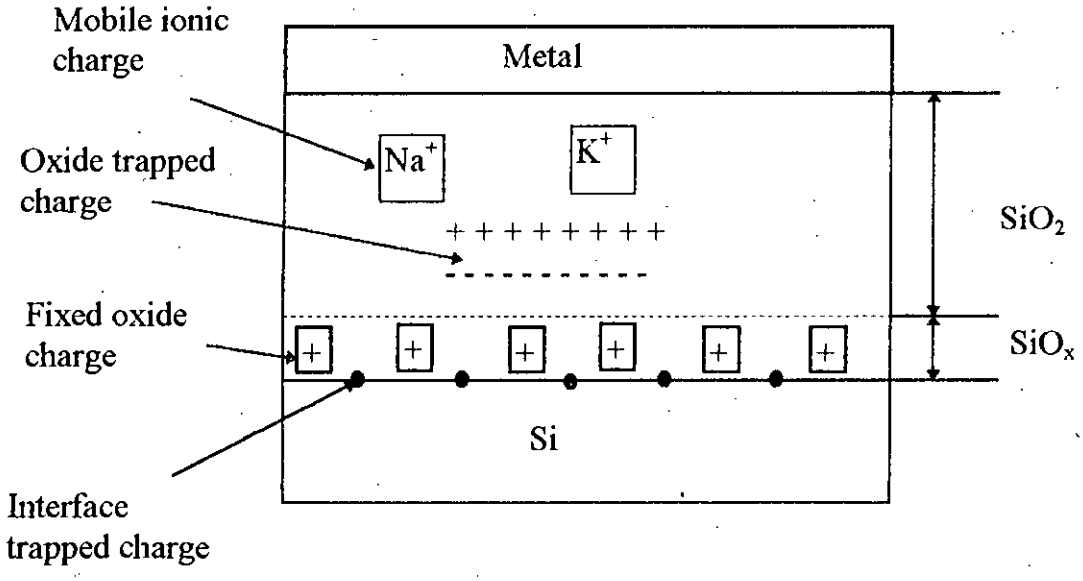


Fig. 2.4 Terminology of charges associated with thermally oxidized silicon

2.4 Creation of oxide traps :

The oxide traps are created during fabrication due to some loose bonds of Si and these are intrinsic traps. Some traps are also created when high energy hot carrier injected into the oxide and break the bonds of SiO_2. The generation of interface trap at the Si/SiO_2 interface and the oxide trapped charge are due to ionizing radiation as well as high field stressing [1,3]. Due to high electric field, carriers that are injected into the depletion layer are accelerated and some of them may gain enough energy to cause impact ionization, [19]. These carriers have higher energy than the thermal energy and are called hot carriers.

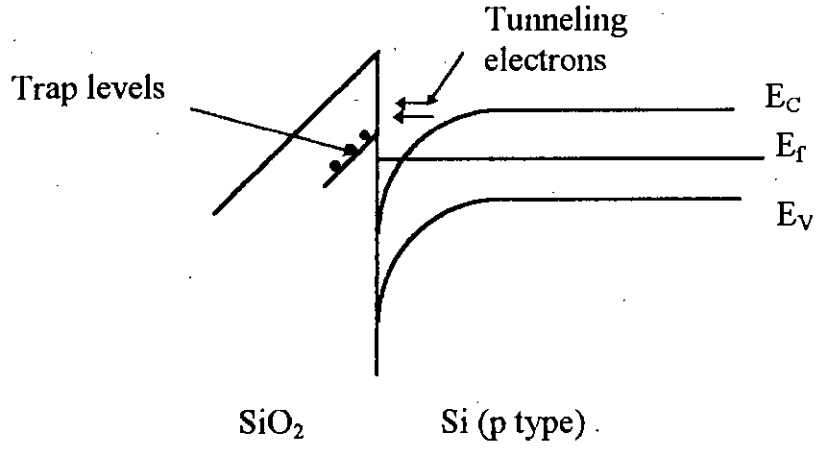


Fig. 2.5 A possible model for detrapping of trapped holes showing electrons tunneling from silicon conduction band to trap levels applying positive gate voltage.

If the hot electrons have energies larger than the Si-SiO_2 energy barrier (3.2 eV) then they can get injected from Si conduction band into the gate oxide. Even if these electrons have energies greater than 1.5 eV they may be able to tunnel into the oxide from inversion layer [19]. Both electron and hole traps results from hole injection, although traps are initially neutral and hence not seen [20]. A fraction of the injected electrons are captured by electron traps in the oxide resulting in trapped negative charges in the oxide [3]. These negative charges influence the device characteristics producing positive shift of threshold voltage. The amount of trapped charge can be calculated from the shift of the threshold voltage if the position of charge centroid is known. Due to oxide trapped charge the transconductance becomes smaller because of reduced channel mobility [18].

A possible microscopic mechanism for trap generation is that a hot electron (having energies lager than 3.7 eV) breaks a silicon-hydrogen bond [21]. If the trivalent Si atom recombine with hydrogen, no interface trap is generated. If the hydrogen atom

diffuses away from the interface, a new interface trap is generated [21]. In insulator - semiconductor device structures, the bonds that can be readily broken are[22]: (1) the strained intrinsic bonds, such as Si-O~Si~O-Si where, ~ indicates a strained bond, in the sense that the bond length ~ is stretched or longer than the average and hence susceptible to rupture or breakup by an impinging energetic electron; (2) the hydrogen bond at a proton trap such as SiO-H, Si-H and Si.H.X≡Si_3 where X is a group III acceptor such as B, Al, Ga, or In; and (3) weak impurity bonds.

2.5 Effects of oxide trapped charge :

The main effect of oxide trapped charge is a definite shift in threshold voltage of the device. It causes also a voltage shift of the MOS Capacitance-Voltage (C-V) curve. These oxide traps are associated with defects in SiO_2 . These oxide traps are usually electrically neutral and are charged by introducing electrons and holes into the oxide. Fig. 2.6 shows the band diagram and the charge distribution for an MOS diode with both fixed oxide charge and oxide trapped charge. Comparing this Fig. 2.6 with Fig.2.2, it can be noted that for the same surface potential ψ_s , the applied voltage V_G is reduced which makes the threshold voltage shift .

The shift due to the oxide trapped charge is given by [18],

$$\Delta V_{ot} = \frac{Q_{ot}}{C_o} = (1/C_o)[\,(1/t_{ox})\int_0^{t_\alpha} x\rho_{ot}(x)dx] \qquad (2.10)$$

where,

Q_{ot} = effective net charge in the bulk oxide traps per unit area at the Si-SiO_2 interface.

$\rho_{ot}(x)$ = volume oxide trap density.

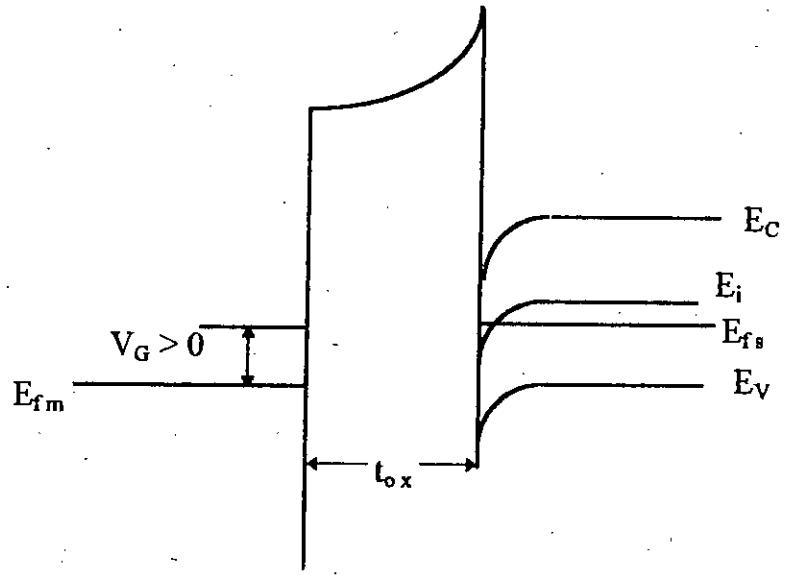


Fig. (a)

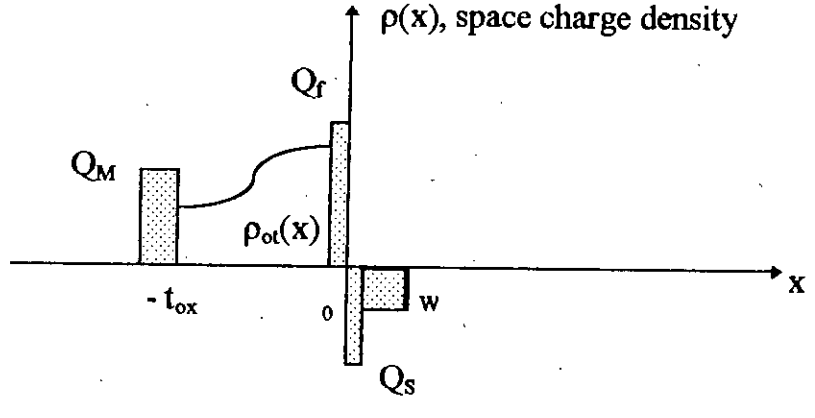


Fig. (b)

Fig. 2.6 (a) Band diagram and (b) Charge distribution with fixed oxide charge and oxide trapped charge of a MOS diode.

Even after detrapping of oxide trapped charge on the application of an electric field , the remaining flat band voltage shift $\Delta V(t)$ is given by [7]

$$\Delta V(t) = \frac{qt_{ox}}{\varepsilon_{ox}\varepsilon_o}\int_0^{t_{ox}}\left(1-\frac{x}{t_{ox}}\right)n_o(x)e^{\frac{-t}{\tau(x,F)}}dx \qquad (2.11)$$

where,

$\tau(x,F)$ = time constant of oxide trapped charge on the applied electric field.

$n_o(x)$ = initial distribution of filled traps .

2.6 Discussion :

Due to the continuous scaling down of MOSFET device dimensions, both the lateral and the transversal electric fields generated during device operation are steadily increasing. This enhances the injection of channel hot carriers, thus aggravating the problem of oxide trapping and interface state generation. Long-term operation of the device is seriously affected by oxide charging, because the charging continues to increase with time during device operation. As a result of this cumulative degradation, oxide charging limits the maximum voltage levels that can be applied for a given specific device life time. To reduce oxide charging the water related traps in the oxide should be minimized.

CHAPTER-3

QUANTUM MECHANICAL TUNNELING PHENOMENA AND THE METHOD OF SOLUTION

3.1 Introduction :

An estimation of the quantum mechanical transmission coefficient (QMTC) across the arbitrary quantum-barrier and quantum-well structures are required to understand the physical mechanisms and the major features of resonant tunneling process. The quantum mechanical transmission coefficient and hence the quantum mechanical reflection coefficient (QMRC) can be calculated by solving the single particle, one dimensional time independent Schrodinger wave equation with scattering wave conditions. [11]. The closed form analytic solutions in terms of known functions can be obtained only for certain special forms of potential energy profiles. When an exact analytic solution of the Schrodinger equation across a particular potential is not available, approximate method applicable to general potentials is required.

The WKB approximation is the conventional method of determining QMTC [13]. Although it is conceptually elegant, it is nevertheless an approximation scheme that does not take into account , for example, the detailed structure of a given potential below the penetrating electron energy level. The WKB method fails to show the fine structure of

the QMTC. Furthermore, it predicts incorrect resonant energies of a resonant system. The WKB method is a quasi-classical approximation and is valid when the De-Broglie wavelengths of electrons are small compared to the distance over which the potential changes appreciably.

The QMTC is calculated by Chandra and Eastman [23] for a triangular barrier via the numerical method using Taylor series expansions for the wave function and it's derivative. This method can also be extended for arbitrary structures but the computation will be inefficient.

In another approach, the potential structure is approximated either piecewise linear potential functions or, by piecewise constant potential functions. The solutions of Schrodinger wave equation in a region can then be expressed as a linear combination of plane or evanescent waves. The general concept of quantum mechanical tunneling is discussed in sec.3.2. A simple method of calculating the QMTC of tunnel structure is presented in sec.3.3. A method for calculating the wave function is present in sec. 3.4.

3.2 Review of quantum mechanical tunneling :

Let us consider a finite one-dimensional potential barrier V(x) between two constant potential energy regions which are semi-infinite in extent as shown in Fig. 3.1. According to the theory of classical mechanics a stream of particles coming from the left with energies E less than the barrier peak V_p will be totally reflected but with energy $E>V_p$ completely transmitted. According to quantum theory, any particle can be represented by a wave. However, because of the wave nature of the matter, the probability of reflection is finite for $E>V_p$, and the possibility of tunneling exists for $E<V_p$.

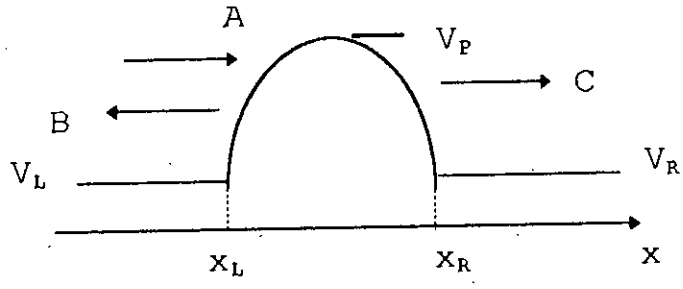


Fig 3.1 A one dimensional potential barrier V(x)

An electron wave with energy E incident on the barrier from left to right is represented by the stationary wave function,

$$\psi_i(x) = Ae^{-jk_i x}, \quad x < x_L \tag{3.1}$$

where,

A is a complex constant and

K_i is the wave vector for the region, $x < x_L$

The wave vector K can be determined by using the equation,

$$K(E,V) = \frac{p}{\hbar} = \sqrt{\frac{2m^*(E-V)}{\hbar^2}} \tag{3.2}$$

so that,
$$K_i = K(E,V_L) = \frac{p}{\hbar} = \sqrt{\frac{2m^*(E-V_L)}{\hbar^2}} \tag{3.3}$$

where,

P is the momentum.

m^* is the effective mass.

V_L is the height of the potential to the left of the barrier.

$\hbar$ is reduced Planck's constant.

The reflected and transmitted waves are represented by the expression

$$\psi_r(x) = B\, e^{jk_t x} \qquad , x < x_L \tag{3.4}$$

$$\psi_t(x) = C\, e^{-jk_t x} \qquad , x > x_R \tag{3.5}$$

respectively.

Where, $k_t = k(E, V_R)$ is the wave vector for $x > x_R$ and B and C are complex constants.

The current transmission coefficient D is equal to the ratio of the transmitted current to the incident current [24].

$$D = \frac{k_t |C|^2}{k_i |A|^2} \text{ , assuming same effective mass.} \tag{3.6}$$

The reflection coefficient R is then just the ratio of the intensities of reflected and incident waves [24].

$$R = \frac{|B|^2}{|A|^2} \tag{3.7}$$

The two coefficients are related by [24]

$$R + D = 1 \tag{3.8}$$

D and R are the functions the electron energy for a given potential barrier V(x). D and R are independent of the direction from which the electron is incident on the barrier.

D(E) and R(E) may be determined by solving the time independent Schrodinger wave equation,

$$\frac{d^2\psi}{dx^2} + \frac{2m^*[E - V(x)]\psi}{\hbar^2} = 0 \tag{3.9}$$

using the conditions of continuity of ψ and $\frac{d\psi}{dx}$.

3.3 Methodology :

3.3.1 Quantum mechanical transmission probability across arbitrary potential structures - The generalized impedance concept :

A straight forward method for solving the time independent Schrodinger wave equation to calculate the QMTC across an arbitrary one-dimensional potential well have been developed by Khondker et. al. [17]. This method is based on the analogy between the plane wave and evanescent wave solutions of Schrodinger's equation in a region of constant potential and the waves along a uniform transmission line. A quantum mechanical wave impedance analogous to the impedance in transmission lines have been defined to make use of impedance transformation and other complex impedance matching techniques in the design and analysis of resonant tunneling and other so called quantum size effect devices.

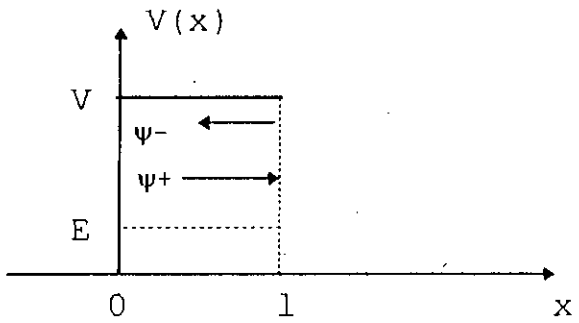


Fig. 3.2 A region with constant potential energy V

To understand the concept of quantum mechanical wave impedance in analytical form let us consider a region of constant potential and the solution of one-dimensional

time independent Schrodinger wave equation in this region. The wave function in the region $0 < x < l$ (Fig. 3.2) associated with energy E incident normally on the potential barrier is,

$$\psi(x) = \psi^{+} e^{\gamma x} + \psi^{-} e^{-\gamma x} \tag{3.10}$$

where,

$$\gamma = \alpha + j\beta = j\sqrt{\frac{2m^{*}(E - V)}{\hbar^{2}}} \tag{3.11}$$

is the propagation constant; m^{*} is the effective mass and $\hbar$ is the reduced Planck constant. ψ^{+} and ψ^{-} are the complex constants.

Now consider a function Φ which is defined as

$$\Phi = \frac{2\hbar}{jm^{*}} \frac{d\psi}{dx} \tag{3.12}$$

$$= \frac{2\hbar}{jm^{*}} \gamma (\psi^{+} e^{\gamma x} - \psi^{-} e^{-\gamma x})$$

$$= Z_{o} (\psi^{+} e^{\gamma x} - \psi^{-} e^{-\gamma x}) \tag{3.13}$$

where, $Z_{o} = \frac{2\hbar}{jm^{*}} \gamma$

The equations for the current (I) and the voltage (V) in a uniform transmission line with distributed impedances have the form [25] :

$$I(x) = (I^{+} e^{\gamma_t x} + I^{-} e^{-\gamma_t x}) \tag{3.15}$$

$$V(x) = Z_{ot} (I^{+} e^{\gamma_t x} - I^{-} e^{-\gamma_t x}) \tag{3.16}$$

where, γ_t is the propagation constant; Z_{ot} is the characteristic impedance of the transmission line.

Comparison of equations (3.10) and (3.13) with equations (3.15) and (3.16) shows that ψ and Φ are analogous to current I and voltage V, respectively in a transmission line. Thus, Z_o can be regarded as a characteristic wave impedance for the region $0 < x < l$. We must consider the continuity conditions at the interface between two adjacent regions to complete the analogy. At the interface, particle conservation requires the continuity of ψ and the continuity of $\frac{1}{m^*} \frac{d\psi}{dx}$. The second condition is slightly different from what is often used in that the derivative of the wave function is divided by the effective mass. Therefore, the continuity conditions will be satisfied if ψ and Φ are continuous everywhere including the interfaces. These conditions corresponds to those transmission lines which require that total voltage and current be continuous at the junction between two transmission lines.

Again, the ratio of Φ and ψ are analogous to the ratio of voltage and current which is called impedance. This ratio (Φ /ψ) is most useful because the techniques devised for transmission line computation may be applied to problems in resonant tunneling phenomena. The quantum mechanical wave impedance (QMWI) at any plane x is defined as,

$$Z(x) = \Phi(x) / \psi(x) \tag{3.17}$$

This ratio is simply Z_o for a (+)vely traveling wave at all planes whereas for a negatively traveling wave this ratio is - Z_o for all x. In general, the QMWI will vary with x. The input impedance value Zin= Z(0) distance l in front of a plane at which the load value of QMWI is given as $Z_L = Z(l)$ may be derived in a manner similar to the corresponding transmission line formula [25].

$$Z_{in} = Z_o \frac{Z_L \cosh \gamma l + Z_o \sinh \gamma l}{Z_o \cosh \gamma l + Z_L \sinh \gamma l} \tag{3.18}$$

where, Z_o is the characteristic QMWI of the intervening region.

The equation (3.18) constitutes the core of the exact solution of Schrodinger's equation across arbitrary piecewise constant potential. By using the analogy the equation for reflection coefficient defined as the ratio of the voltage in the reflected wave to that in the incident wave [25] gives the wave amplitude reflection coefficient $\rho = \psi^-/\psi^+$ for a potential structure of characteristic impedance Z_o when it is terminated with some known load value of QMWI Z_L :

$$\rho = \frac{Z_L - Z_o}{Z_L + Z_o} \tag{3.19}$$

The probability current density S [19] can be defined as,

$$S = \mathrm{Re}\left[\psi^* \frac{\hbar}{jm^*} \frac{d\psi}{dx} \right]$$

$$= (1/2)\,\mathrm{Re}[\Phi\psi^*] \tag{3.20}$$

Thus, S is analogous to the average power in transmission lines.
Therefore, the use of equation (3.18) makes the wave impedance method computationally efficient for analyzing arbitrary potential functions.

3.3.2 Application of impedance method for an arbitrary potential function :

This requires the continuous variations of potential energy which is to be approximated by piecewise-constant functions. Consider the potential function as show in Fig.3.3 be splitted up into a sequence of N small segments. Then the effective electron mass $m^*(x)$ and the potential barrier V(x) are approximated by the multistep functions.

$$m^*(x) = m_i^*(x) = m^*[x_{i-1}+x_i]/2 \tag{3.21}$$

$$V(x) = V_i = V[x_{i-1}+x_i]/2 \tag{3.22}$$

for , $x_{i-1} \leq x < x_i$ (i=1,2,3.....N)

Consider the left ($x < x_o$) and the right ($x > x_N$) of the potential barrier which can be assumed to seminfinite in extent.

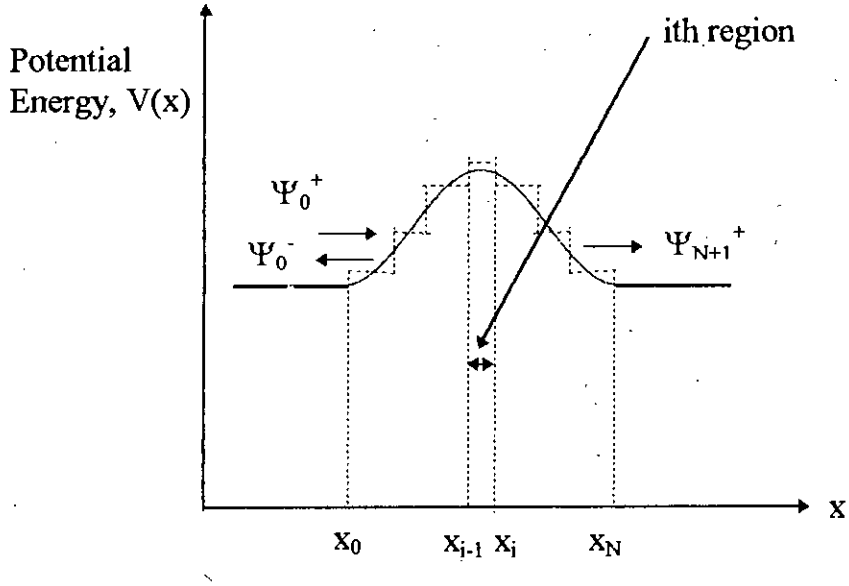


Fig.3-3. Energy band diagram (Solid line) and approximated potential functions (broken line) for the potential barrier.

Suppose we shall calculate the QMTC of an electron incident with energy E at the left side of the barrier. The estimation of the QMTC across the barrier has been reduced to the calculation of the QMWI for the electron streaming from the left toward the barrier using equation (3.18). The values of γ and Z_o in different segments can be calculated using equation (3.11) & (3.14) respectively. Since there is no reflected wave in the region $x > x_N$ it can be represented by a transmission line of infinite length.

The load impedance $Z_L = Z(x_N)$ is equal to $Z_{o,\,N+1}$, the characteristic impedance of the (n+1)th region. The impedance $Z(x_{N-1})$ is calculated using equation (3.18) with $Z_o = Z_{o,N}$, $l = x_N - x_{N-1}$ and this process is repeated until the impedance $Z(x_o)$ is obtained.

$$Z(x_{i-1}) = Z_{o,i}\frac{Z(x_i)\mathrm{Cosh}\gamma_i l_i + Z_{o,i}\mathrm{Sinh}\gamma_i l_i}{Z_{o,i}\mathrm{Cosh}\gamma_i l_i + Z(x_i)\mathrm{Sinh}\gamma_i l_i} \tag{3.23}$$

where,

$$\gamma_i = \alpha_i + j\beta_i = j\sqrt{\frac{2m_i^*(E - V_i)}{\hbar^2}} \tag{3.24}$$

$$l_i = x_i - x_{i-1} \tag{3.25}$$

The wave impedance reflection coefficient ρ at $x = x_o$ is calculated by using $Z(x_o)$ as the load impedance and $Z_{o\,,\,o}$ as the characteristic impedance and substituting these values in equation (3.19). The QMTC D(E) is then given by [17].

$$D(E) = 1 - |\rho(E)|^2 \tag{3.26}$$

Where $|\rho(E)|^2$ is the quantum mechanical reflection coefficient.

3.4 Solution for the wave function :

The wave function in any region of constant potential can be calculated using equation (3.10). The solutions of two adjacent region must then be connected at the interface using the continuity conditions. For automatic solution matching at potential discontinuities and ease of numerical computation it is convenient to write the wave function in the i th region as

$$\Psi(x) = \Psi_i^+ \left[e^{\gamma_i (x - x_i)} + \rho^-(x_i) e^{-\gamma_i (x - x_i)} \right] \tag{3.27}$$

where, $\rho^-(x_i) = \frac{\Psi_i^-}{\Psi_i^+}$ is the reflection coefficient at $x = x_i^-$

putting $x = x_i$ in equation (3.27) we get,

$$\Psi_i^+ = \frac{\Psi(x_i)}{1 + \rho^-(x_i)} \tag{3.28}$$

From equation (3.27) and (3.28) we finally get

$$\Psi(x) = \Psi(x_i) \left[Cosh\{\gamma_i (x - x_i)\} + \frac{1 - \rho^-(x_i)}{1 + \rho^-(x_i)} Sinh\{\gamma_i (x - x_i)\} \right] \tag{3.29}$$

$$= \Psi(x_i)\left[\mathrm{Cosh}\{\gamma_i (x - x_i)\} + \frac{Z(x_i)}{Z_{o,i}} \mathrm{Sinh}\{\gamma_i (x - x_i)\} \right] \qquad (3.30)$$

for, $x_{i-1} \le x \le x_i$

From equation (3.30) the following recurrence relation can be obtained

$$\Psi(x_{i-1}) = \Psi(x_i)\left[\mathrm{Cosh}(\gamma_i l_i) - \frac{Z(x_i)}{Z_{o,i}} \mathrm{Sinh}(\gamma_i l_i) \right] \qquad (3.31)$$

The solution of ψ throughout the structure entails an initial condition. We can freely choose an initial condition that is convenient for an unbounded function. $|\rho|^2$ is unaffected by this choice of initial condition as it is the ratios of square of amplitudes and so the absolute normalization of free particle wave functions is not required. A convenient initial condition is to assume $|\Psi(x_N)| = 1.0$; the recurrence relation equation (3.31) can then be used to determine at each position over the full region with which we are interested.

In some cases the position probability density $|\Psi|^2$ rather than the wave function ψ it self is of physical importance. A much simpler method for accurately calculating $|\Psi|^2$ can then by developed for an unbounded wave function.

Using equation (3.17) the probability current density S in equation (3.20) is expressed simply by

$$S(x) = \frac{1}{2} \mathrm{Re}[\, Z(x)\, \psi(x)\, \psi^*(x)\,]$$

$$= \frac{1}{2}|\Psi(x)|^2 \ \mathrm{Re}[Z(x)] \tag{3.32}$$

S represents the net electron flux and for a stationary problem it must be independent of x .

If we assume $|\Psi(x_N)| = 1.0$ then at $x = x_N$, S has the value $\frac{\hbar \beta_{N+1}}{m^*_{N+1}}$.

where,

$$\beta_{N+1} = \sqrt{\frac{2m^*_{N+1}(E - V_{N+1})}{\hbar^2}} \tag{3.33}$$

$|\Psi|^2$ at any x is then given by ,

$$|\Psi(x)|^2 = \frac{2\hbar\beta_{N+1}}{m^*_{N+1}\,\mathrm{Re}[Z(x)]} \tag{3.34}$$

3.5 Discussion :

A simple but exact method of solving the Schrodinger equation for a piecewise constant potential has been presented by Khondker et. al. [17]. Since any potential function can be approximated by using piecewise constant potential function to arbitrary accuracy, then Schrodinger equation can be solved to any degree of accuracy for various potential barriers and wells including continuous variations of potential and effective mass. Various useful quantum mechanical quantities regarding the particular potential can be obtained by using the solution. In the next chapter, this quantum mechanical wave impedance concept will be used to estimate the life time of oxide trapped charge at various distance throughout the oxide length of the MOS structure .

CHAPTER 4

TIME DEVELOPMENT OF THE OXIDE TRAPPED CHARGE IN AN MOS STRUCTURE

4.1 Introduction :

The investigation of the time development of tunneling phenomenon is important since it determines not only the fundamental frequency limit of most devices involving resonant tunneling but also the mechanism for the physics of the tunneling process.

There is an interesting property of resonant tunneling structure for transmitting electrons through a quantum well sandwiched between two potential barriers with high transmission probability when the electrons are incident at energies equal to any of the virtual energy levels of the well[26]. Electrons having energies other than the virtual energies of the well have a very low transmission coefficient i.e., they are not allowed to pass through the resonant tunneling (RT) structure. The build up of a coherent electron wave function in the quantum well involves a process very similar to that building up an electromagnetic wave in a Febry-perot resonator [27]. In the absence of a scattering mechanism, which can destroy the phase coherence of electron wave, the amplitude of the resonant modes builds up in the quantum well. The electron waves can leakout in both directions and in doing so cancel the reflected waves and thus enhance

the transmitted wave [26]. If the time evolution of the wave function in the well is long compared to the scattering time, the collisions randomize the phase of the wave function. In this case, the electrons tunnel through both the barriers sequentially and the RT structure has a lower quantum mechanical transmission peak.

Tunnel injection of charge carriers from traps into the allowed energy bands of insulators, the so called field ionization, is a well-studied phenomenon. One or, more trap energy levels even exist in insulators and direct injection of charge carriers in insulators from an electrode may also occur [9]. In this research, we investigate the tunneling of charge carriers from a metal or, semiconductor to a trap in insulator. This process is important to study the insulator currents and breakdown phenomena. In this chapter , an analytic formula for the life time of oxide trapped charge is derived by considering the electron wave function as one-dimensional delta function . Then this analytic formula is modified to determine the effective life time when the gate voltage is switched from one to another voltage which is less than the initial applied voltage . To determine the effective life time the probability density distribution corresponding to the initial applied voltage is also presented .

4.2 Limitations of frequency for tunneling structures:

The proposed frequency limitations of device involving the tunneling process have been based on various definitions of the intrinsic time scale for the tunneling electrons. These include the life time of resonant state [28], wave packet delay time and resistance-capacitance time constants.

The traversal time is the time during which the tunneling particle is actually traversing the barrier. The importance of traversal time in characterizing the tunneling process have been pointed out by some authors [16,26]. But there are several contradictory results for the traversal time. Buttiker and Landauer [29] have substantiated an existing expression for traversal time by considering tunneling through a time-modulated barrier :

$$\tau_T = \int_{x_1}^{x_2} \frac{m^*}{\hbar k(x)} dx \tag{4.1}$$

x_1 and x_2 are turning points and $K(x) = \sqrt{\frac{2m^*[V_o(x) - E]}{\hbar^2}}$

for the tunneling electrons after the establishment of steady state in DBRTS. Anwar et. al. [26] calculated the traversal time by determining steady state group velocity V_g of the tunneling particles from the equation

$$S(x) = V_g(x) |\Psi(x)|^2 \tag{4.2}$$

where , S is the probability current density through the double barrier resonant tunneling structure (DBRTS) , which at resonance is equal to the incident current density for a symmetric structure and ψ is the steady state wave function .

Comparison of equation (4.2) with equation (3.32) gives us ,

$$V_g(x) = \frac{1}{2} \text{Re } [Z(x)] \tag{4.3}$$

The traversal time is then given by ,

$$\tau_T = \int_0^L \frac{dx}{V_g(x)} \tag{4.4}$$

$$= 2\int_0^L \frac{dx}{Re[Z(x)]} \tag{4.5}$$

where , L is total length of the resonant tunneling structure.

Smith [30] calculated a time τ_d which is the ratio of the number of particles under the potential to the incident flux. This time is the average dwell time of a particle which is not the traversal time, if most particles are reflected [29].

$$\tau_d = \frac{\int_0^L |\Psi(x)|^2 dx}{S_{in}} \tag{4.6}$$

where , S_{in} is the incident flux . For a Symmetric double barrier resonant tunneling structures at resonance $S_{in} = S(x) = V_g(x)|\Psi(x)|^2$ so that τ_d becomes essentially the same as the traversal time τ_T proposed by Anwar et. al.[26]. Luryi [30] calculated the time constant of the transient process during which the resonant modes builds up inside the well due to charging of the 'quantum capacitor' formed between the base quantum well and emitter electrode by the tunneling current through the first barrier. But the frequency limitation calculated by Luryi gives much lower value which is not relevant for usual device operation.

Lundstrom and Svensson [9] calculated the tunneling time constant of oxide trapped charge in an MOS structure by using,

$$\tau = \frac{1}{P} \tag{4.7}$$

where , P is the probability of tunneling through the oxide and is given by ,

$$P = \frac{2\Pi}{\hbar}|T_{rl}|^2 \frac{dn}{dE} \tag{4.8}$$

where , $\frac{dn}{dE}$ is the density of states for the metal and should be taken at $E=E_l$ which is the total energy of the conduction band electron.

$$\text{Tunnel transition , } T_{rl} = \int \Psi_r^* V_\delta \Psi_l \delta(r) dr \tag{4.9}$$

where , the wave function Ψ_r and Ψ_l characterizes a trapped electron and an electron in the conduction band of the metal and V_δ characterizes a three dimensional δ function trap. But Yamabe and Miura [8] calculated the tunneling probability P_{ox} using WKB approximation as ,

$$P_{ox} = e^{-2\int_{x_1}^{x_2} K(x)dx} \tag{4.10}$$

$$\text{and , } \quad \tau = \frac{\tau_0}{P_{ox}} \tag{4.11}$$

where, k(x) is the imaginary part of the longitudinal wave vector in the SiO_2 band gap , τ_0 is the shortest time constant and x_1 , x_2 are the classical turning points.

The detrapping of holes out of SiO_2 in an n-MOSFET's after exposure to ionizing radiation was found to play a dominant role in the long term recovery of irradiated MOS devices [5]. It was modeled as a tunneling transition of holes from an energetic level about 3 eV above SiO_2 valence band. Manzini and Modelli [5] developed an expression for the dependence of the time constant of the hole discharge on the applied electric field F and the distance x between trapped hole and interface which is given by ,

$$\tau(x,F)=\tau_0 \exp\left(\frac{4\sqrt{2m^*}}{3\hbar qF}\left(E_t^{1.5}-(E_t-qFx)^{1.5}\right)\right) \qquad (4.12)$$

where, E_t is the energetic level above the SiO_2 valence band , τ_0 is the characteristic tunneling time and m^* is the hole tunneling effective mass.

4.3 Calculation of life time of oxide trapped charge using stationary state solution :

An alternative analytical formulation , using the stationary state wave function to calculate the life time of an electron in a quantum well is presented here. Consider a simplest case of resonant transmission , when a particle of energy E is incident from left upon two consecutive barriers of height greater than E, with a classically allowed region between them (Fig.4-2). The energy of the particle is almost totally reflected, but in exponentially small energy intervals of width ΔE, the particle transmission is greatly enhanced.

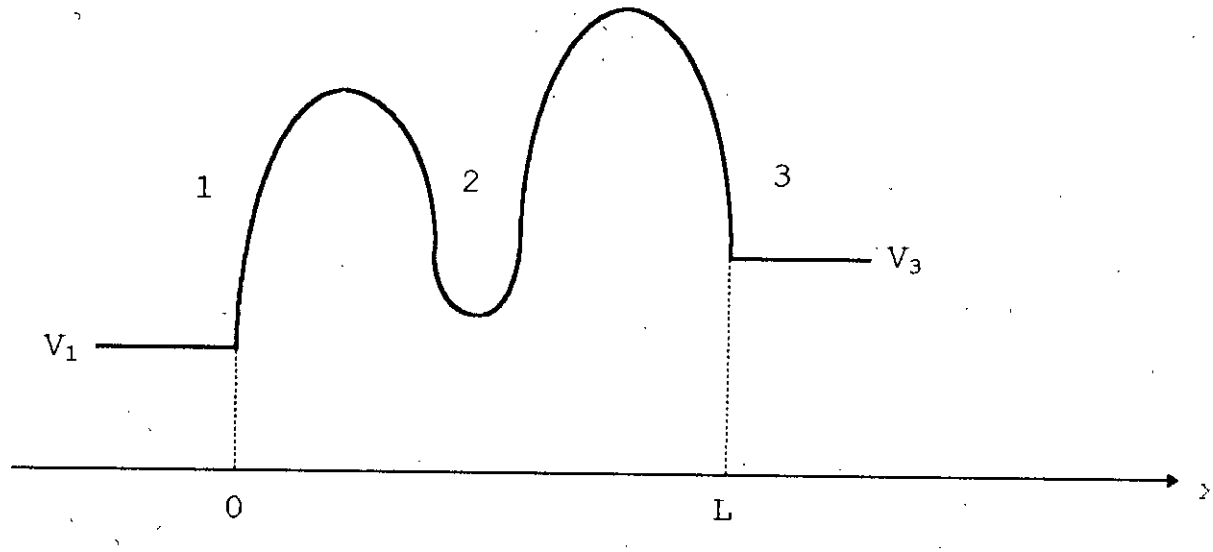


Fig. 4.1 Conduction band profile of a double barrier resonant tunneling structure .

A relatively large electronic density builds up in the allowed region between the barriers, because the wave leaking through the first barrier is constructively interfering with reflections of the second barrier. The final wave function inside the well may be

obtained by summing up all the multiply reflected waves. Let , this stationary wave function be represented by $\psi(x)$ which can be obtained from the solution of time independent Schrodinger's wave equation.

If the incident wave is now stopped, the accumulated charge density in the well will gradually decrease since the carriers will leak through the barriers into region 1 and region 3 . The amplitude of the wave in the well will decrease with time and let this time-varying function be represented as

$$\psi(x , t) = \psi(x)\, f(t) \tag{4.13}$$

where , $f(t) = 1$ at, $t=0$

The wave function in region 1 (for $t > 0$) can be written as,

$$\Psi(x,t) = \Psi(0)\, e^{-j\beta_1 x}\, f(t) \quad , x < 0 \tag{4.14}$$

where ,

$$\beta_1 = \sqrt{\frac{2m_1^*(E - V_1)}{\hbar^2}}$$

Similarly the wave function in region 3 for $t > 0$ is

$$\Psi(x,t) = \Psi(L)\, e^{j\beta_3(x-L)}\, f(t) \quad , x > x_L \tag{4.15}$$

where ,

$$\beta_3 = \sqrt{\frac{2m_3^*(E - V_3)}{\hbar^2}}$$

The time derivative of the integral of position probability density P over any fixed volume V is given by [10]

$$\frac{\partial}{\partial t}\int_{v} P(\bar{r},t)\,dv = -\int_{A} \bar{s}.\,\bar{dA} \qquad (4.16)$$

where, A is the bounding surface of the volume V. For the one dimensional structure, equation (4.16) can be written as

$$\frac{\partial}{\partial t}\int_{0}^{L} P(x,t)\,dx = S(0,t) - S(L,t) \qquad (4.17)$$

where, S(0,t) and S(L,t) are the probability current densities at x =0 and x=L, respectively.

The probability current density S is defined as [10]

$$S(r,t) = \frac{\hbar}{2jm^*}\left[\Psi^*\nabla\Psi - (\nabla\Psi^*)\Psi\right] \qquad (4.18a)$$

$$= \text{Real part of}\left[\Psi^* \frac{\hbar}{jm^*}\nabla\Psi\right] \qquad (4.18b)$$

For the one dimensional case,

$$\text{S(x,t)} = \text{Real part of}\left[\Psi^* \frac{\hbar}{jm^*}\frac{\partial\Psi}{\partial x}\right] \qquad (4.19)$$

Therefore from equations (4.14) , (4.15) and (4.16) ,

$$S(0,t)=\frac{-\hbar\beta_1}{m_1^*}|\Psi(0)|^2\,|f(t)|^2 \tag{4.20a}$$

and

$$S(L,t)=\frac{-\hbar\beta_3}{m_3^*}|\Psi(L)|^2\,|f(t)|^2 \tag{4.20b}$$

Substitution of equation 4.20 into equation 4.17 gives

$$\begin{aligned}&\frac{\partial}{\partial t}\int_0^L|\Psi(x)|^2\,|f(t)|^2\,dx\\ =\;&\frac{-\hbar\beta_1}{m_1^*}|\Psi(0)|^2|f(t)|^2+\frac{\hbar\beta_3}{m_3^*}|\Psi(L)|^2|f(t)|^2\end{aligned} \tag{4.21}$$

As f(t) is independent of x equation (4.21) can be written as,

$$\frac{\partial}{\partial t}|f(t)|^2=\frac{-1}{\tau_L}|f(t)|^2 \tag{4.22}$$

where,

$$\tau_L=\frac{\int_0^L|\Psi(x)|^2\,dx}{\frac{\hbar\beta_1}{m_1^*}|\Psi(0)|^2+\frac{\hbar\beta_3}{m_3^*}|\Psi(L)|^2} \tag{4.23}$$

The form of equation (4.23) suggests that τ_L can be taken as the time constant for the decay of the charge density in the well i.e., the life time of the quasi bound state.

For a symmetric double barrier structure τ_T (τ_d) is twice the value of the life time τ_L as can be seen from an inspection of equations (4.6) and (4.23). Here Anwar et. al. [22] suggested an intriguing possibility. If one assume that time required for the electronic density to build up in the well is equal to the decay time then the traversal time of an electron through the RT structure is $2\tau_L$.

Now using equation (4.23) the calculation of life time of oxide trapped charge (e^-) is presented below.

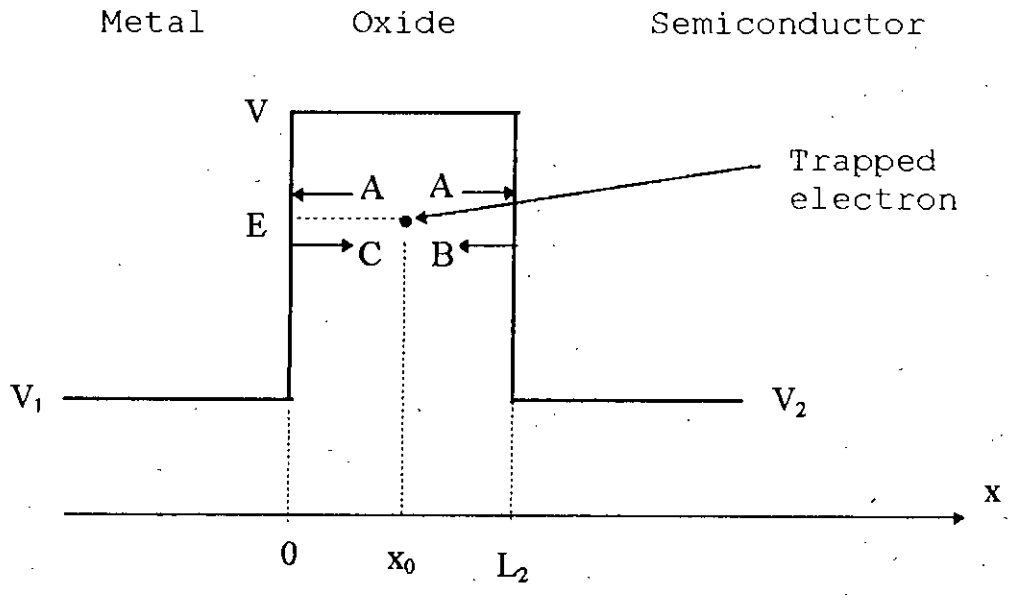


Fig. 4.2 Band diagram of MOS structure at flat band condition .

At first consider that no voltage is applied to the gate i.e., the oxide conduction band is flat. Although, due to some trap charge a small tilt in the oxide conduction band exists but

we can neglect this. Let us, consider an electron is trapped at a distance x_0 from the metal oxide interface (Fig. 4.2). Consider the corresponding trap wave function as,

$$\Psi(x) = Ae^{\gamma(x-x_0)} + Be^{-\gamma(x-x_0)} + Ce^{\gamma(x-x_0)} \tag{4.24}$$

where ,

A , B and C are complex constants and

$$\gamma = \sqrt{\frac{2m^*(V-E)}{\hbar^2}} = \sqrt{\frac{2m^*E_t}{\hbar^2}}$$

m^* = effective mass of electron in SiO_2 layer = 0.1 m_0

m_0 = rest mass of electron = 9.1095×10^{-31} Kg

V = potential barrier height (conduction band of SiO_2)

E = electron energy

E_t = V-E = trap depth

$\hbar$ = reduced Planck constant = 1.055×10^{-34} J-sec

Now ,

$$\begin{aligned} &\int_0^{L_2} |\Psi(x)|^2 \, dx \\ &= \int_0^{x_0} A^2 e^{-2\gamma(x-x_0)} \, dx + \int_{x_0}^{L_2} A^2 e^{2\gamma(x-x_0)} \, dx \\ &+ \int_0^{L_2} B^2 e^{-2\gamma(x-x_0)} \, dx + \int_0^{L_2} C^2 e^{2\gamma(x-x_0)} \, dx \end{aligned} \tag{4.25}$$

$$= \frac{A^2}{2\gamma}\left[\left(-2+e^{2\gamma x_0}+e^{2\gamma L_1}\right)+\frac{B^2}{A^2}\left(-e^{-2\gamma L_1}+e^{2\gamma x_0}\right)+\frac{C^2}{A^2}\left(e^{2\gamma L_1}-e^{-2\gamma x_0}\right)\right] \qquad (4.26)$$

where,

$L_1 = L_2 - x_0$

L_2 = width of oxide layer .

Again , the reflection coefficient at Si / SiO_2 interface ρ_r is ,

$$\rho_r = \frac{B\, e^{-\gamma(L_2-x_0)}}{A\, e^{\gamma(L_2-x_0)}} = \frac{B}{A} e^{-2\gamma L_1}$$

$$\Rightarrow \frac{B^2}{A^2} = \rho_r^2\, e^{4\gamma L_1} \qquad (4.27)$$

the reflection coefficient at metal / SiO_2 interface ρ_l is ,

$$\rho_l = \frac{C\, e^{\gamma(0-x_0)}}{A\, e^{-\gamma(0-x_0)}} = \frac{C}{A} e^{-2\gamma x_0}$$

$$\Rightarrow \frac{C^2}{A^2} = \rho_l^2\, e^{4\gamma x_0} \qquad (4.28)$$

By putting these values in equation (4.26) we get ,

$$\int_0^{L_2} |\Psi(x)|^2 dx = \frac{A^2}{2\gamma}\left[\left(-2+e^{2\gamma x_0}+e^{2\gamma L_1}\right)+\rho_1^2\left(-e^{2\gamma L_1}+e^{2\gamma(x_0+2L_1)}\right)\right.$$
$$\left.+\rho_1^2\left(e^{2\gamma(L_1+2x_0)}-e^{2\gamma x_0}\right)\right] \qquad (4.29)$$

Now ,

$$|\Psi(0)|^2 = \left|Ae^{-\gamma(0-x_0)}+Ce^{\gamma(0-x_0)}\right|^2$$

$$= A^2 e^{2\gamma x_0}\left|1+\rho_1\right|^2 \qquad (4.30)$$

and ,

$$|\Psi(L_2)|^2 = \left|Ae^{\gamma(L_2-x_0)}+Be^{-\gamma(L_2-x_0)}\right|^2$$

$$= A^2 e^{2\gamma L_1}\left|1+\rho_r\right|^2 \qquad (4.31)$$

According to equation (4.23) the life time of oxide trapped charge is,

$$\tau_L = \frac{\int_0^{L_2}|\Psi(x)|^2 dx}{\frac{\hbar\beta_l}{m_l^*}|\Psi(0)|^2+\frac{\hbar\beta_r}{m_r^*}|\Psi(L_2)|^2} \qquad (4.32)$$

where ,

$$\beta_l = \sqrt{\frac{2m_l^*(E-V_1)}{\hbar^2}} \qquad \text{and,} \qquad \beta_r = \sqrt{\frac{2m_r^*(E-V_2)}{\hbar^2}}$$

m_l^* = effective mass of electron in metal

m_r^* = effective mass of electron in semiconductor

E = trapped electron energy

V_1 = conduction band of metal

V_2 = conduction band of Si

The wave amplitude reflection coefficients are given as ,

$$\rho_l = \frac{Z_0 - Z_{Ll}}{Z_0 + Z_{Ll}} \tag{4.33}$$

$$\rho_r = \frac{Z_0 - Z_{Lr}}{Z_0 + Z_{Lr}} \tag{4.34}$$

where,

$Z_0 = \frac{2\gamma\hbar}{jm^*}$, characteristic wave impedance in oxide layer .

Since , $\gamma = j\sqrt{\frac{2m^*(E-V)}{\hbar^2}}$

so , $Z_0 = \sqrt{\frac{E-V}{m^*}}$ (4.35)

Similarly , the load impedance at x = 0 looking toward the left (metal) Z_{Ll} is given by (Fig. 4.3)

$$Z_{Ll} = \sqrt{\frac{E-V_1}{m_l^*}} \tag{4.36}$$

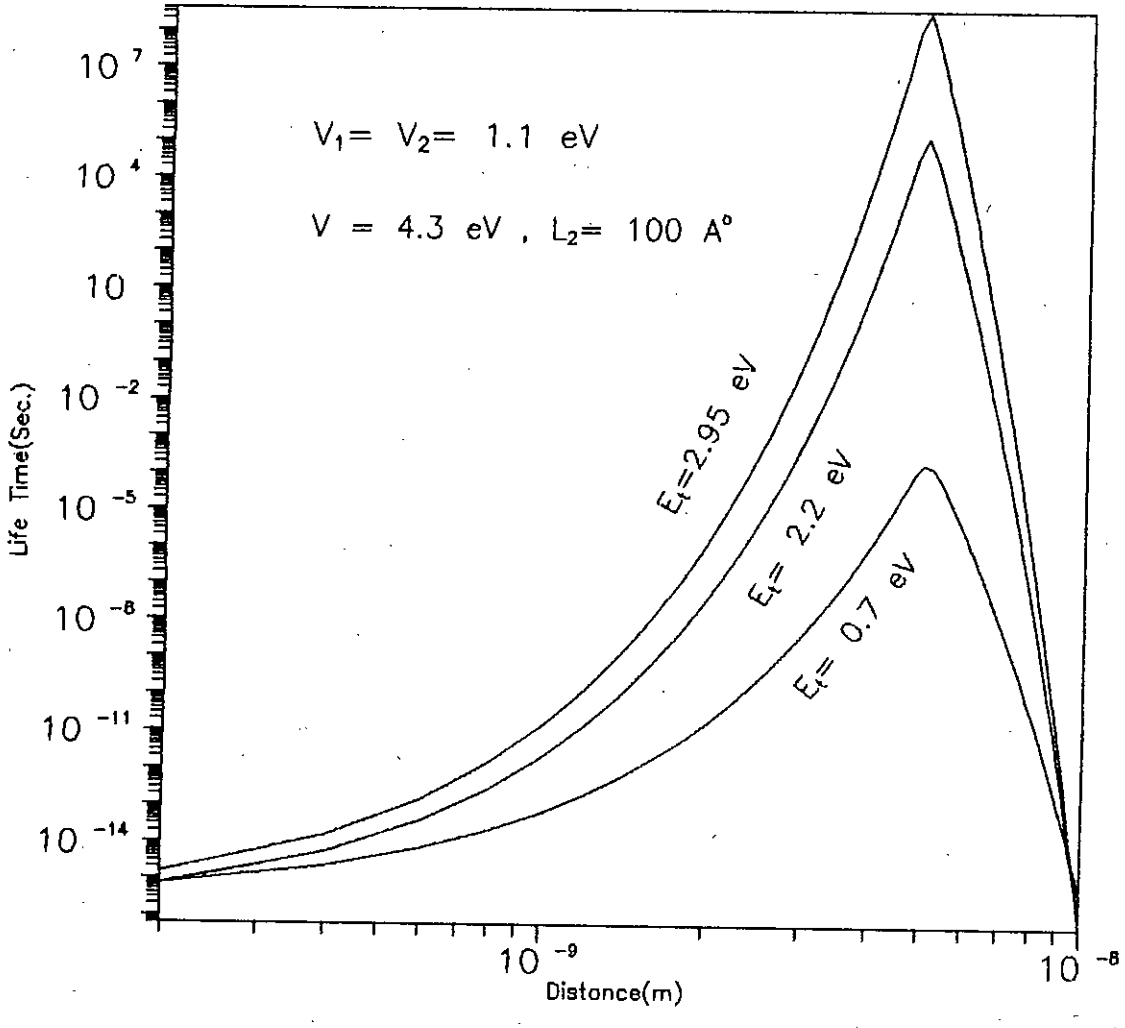


Fig. 4.3 Life time (τ_L) as a function of distance from interface with trap depth (E_t, measured from oxide conduction band) as a parameter.

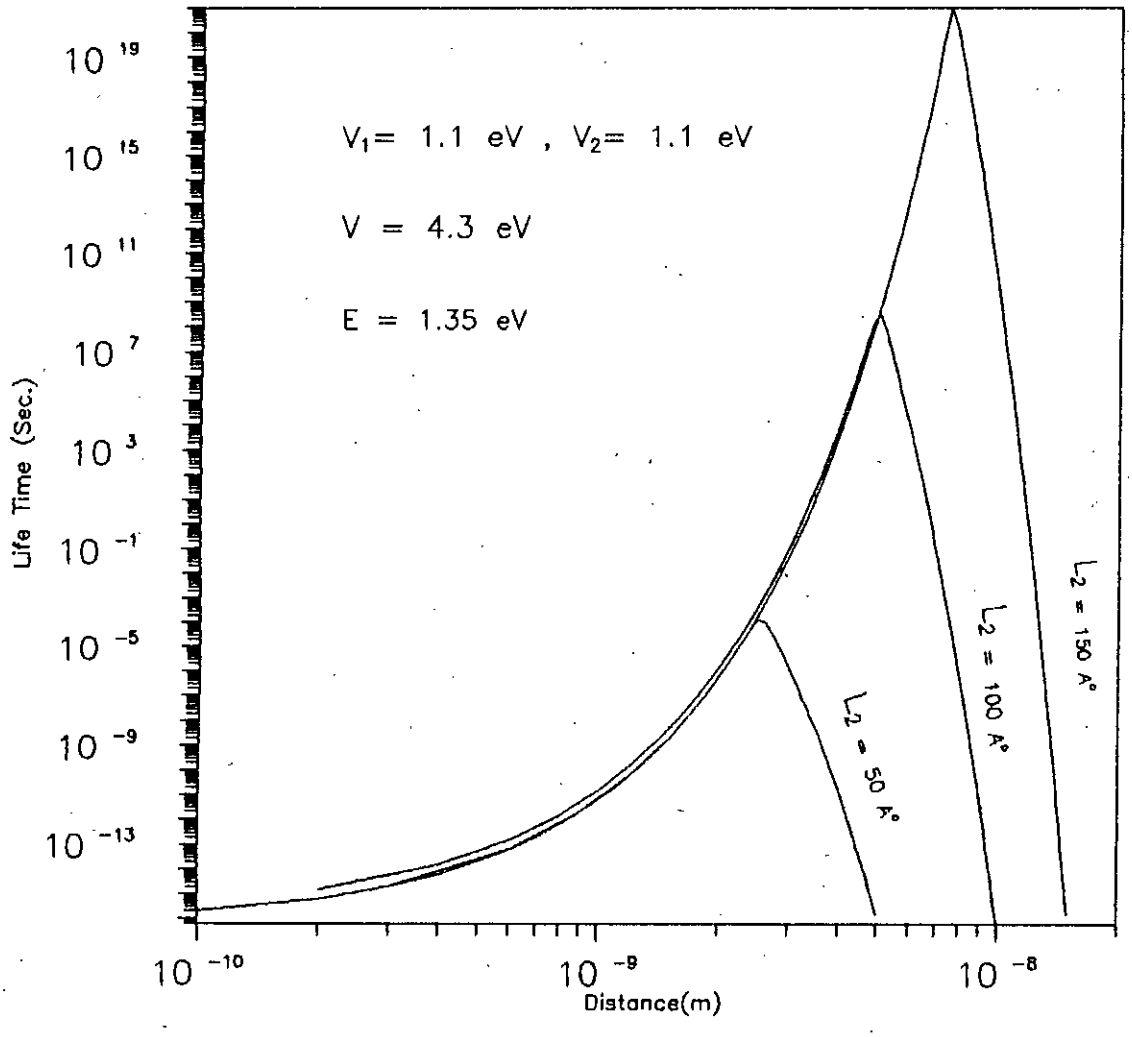


Fig.4.4 Life time (τ_L) as a function of distance from interface with oxide thickness (L_2) as a parameter.

the load impedance at $x = L_2$ looking toward the right (Si) Z_{Lr} is given by (Fig. 4.2)

$$Z_{Lr} = \sqrt{\frac{E - V_2}{m_r^*}} \tag{4.37}$$

Now using equation (4.33) , (4.34) , (4.35) , (4.36) and (4.37) we can calculate ρ_l and ρ_r .

Then, the results obtained by equation (4.32) shows that the states which are more closer to conduction band, that is, the states which have a deep trap depth have longer life times (Fig. 4-3). It is also shown that the life time increases also with the increase in distance from any interface (either metal-oxide or, semiconductor-oxide interface) and it becomes maximum at the middle of the oxide length . It happens because near the interface the tunneling probability is very high and it decreases with the distance from the interface. The maximum life time also increases with the increase in length of the oxide layer (Fig. 4-4). In this analysis the effective electron mass in SiO_2 is assumed to be $0.1m_0$, in Si it is $0.98m_0$ and in metal it is $0.42m_0$. The potential barrier at the Si - SiO_2 interface is assumed to be 3.2 eV.

Now an analytic formulation is presented to determine the effective life time of oxide trap charge by considering that an initial voltage is applied to the gate and then at a moment the gate voltage is switched to another voltage which is less than the initial applied voltage. The effective life time can be determined at the switching moment and for certain delay time T after switching moment.

The bending of oxide conduction band after applying some gate voltage is shown in Fig. 4.5 .Now we can determine the life time of oxide trap charge at various distance throughout the oxide layer by approximating the bending of oxide conduction band as a piecewise constant potential . For each step we can use equation (4.32) but the load impedance at various steps can be determined by using the transformation equation (3.23).

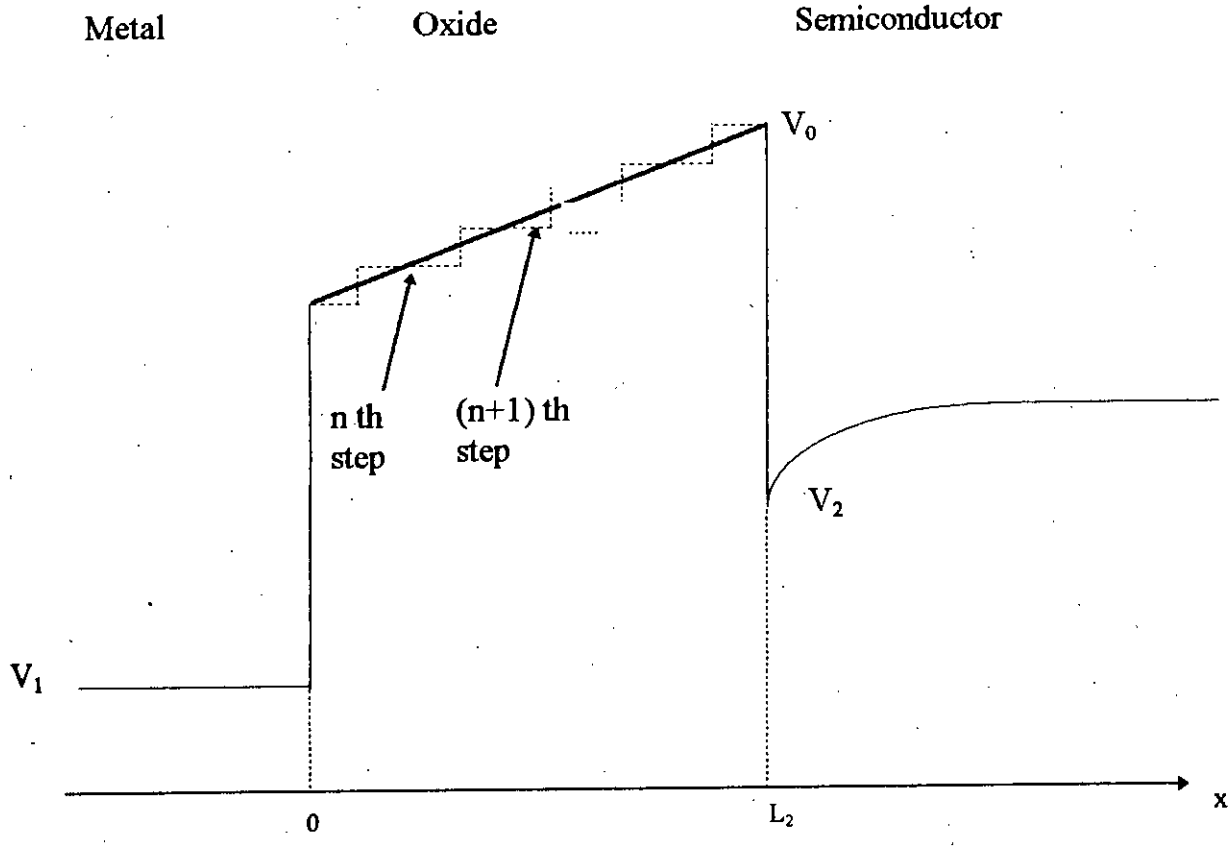


Fig. 4.5 Energy band diagram (solid line) with applied gate voltage and approximation of the oxide conduction band (dotted line).

In this case, the potential barrier height for n th step,

$$V_n = V_0 - V_G + (V_G / L_2)\, x_0 \qquad (4.38)$$

where,

V_G = remaining gate voltage after switching

x_0 = distance of oxide trap from metal-oxide interface

Here, it is assumed that the electrons tunnel with constant energy.

Now to determine the effective life time the wave function distribution, that is, the probability density distribution should be determined. The wave function corresponding to tunneling electrons depends on the initial applied gate voltage.

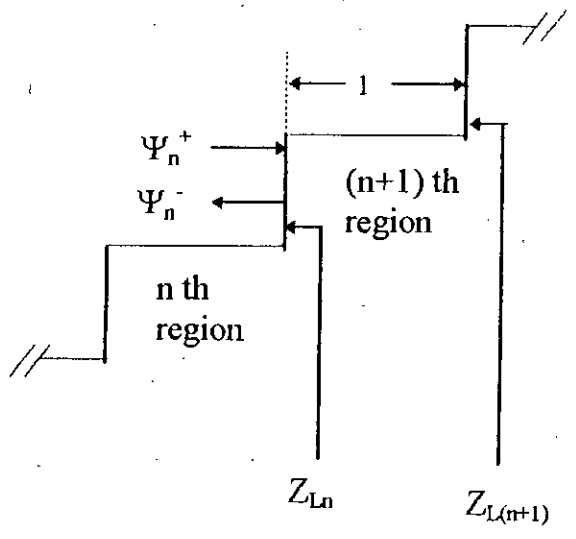


Fig. 4-6. A single step of the approximated oxide conduction band

The wave function in nth region associated with an electron of energy E incident normally on the potential is,

$$\Psi_n(x) = \Psi_n^+ e^{\gamma_n x} + \Psi_n^- e^{-\gamma_n x} \tag{4.39}$$

where,

$$\gamma_n = \sqrt{\frac{-2m^*(E - V_n)}{\hbar^2}} \tag{4.40}$$

V_n = height of the potential barrier (approximated oxide conduction band) of nth region.

V_n can be determined by using equation (4.38) but in this case, V_G is the initial applied gate voltage.

Now,

$$\Psi_n(0) = \Psi_n^+ + \Psi_n^- = \Psi_n^+(1 + \rho_n)$$

$$\text{so, } \Psi_n^+ = \frac{\Psi_n(0)}{1+\rho_n} \tag{4.41}$$

where,

$\rho_n = \frac{\Psi_n^-}{\Psi_n^+}$ is the wave amplitude reflection coefficient for n th region.

ρ_n can be determined by using equation (3.14) , (3.19) & (3.23).

Again,

$$\Psi_{n+1}(0) = \Psi_n(l) = \Psi_n^+\left(e^{\gamma_n l} + \rho_n e^{-\gamma_n l}\right)$$

$$\Rightarrow \Psi_{n+1}(0) = \Psi_n(0)\frac{e^{\gamma_n l} + \rho_n e^{-\gamma_n l}}{1+\rho_n} \tag{4.42}$$

where, l = width of each region.

It is assumed that $\Psi_1(0) = 1.0$ for convenience of calculation. Then we can determine the wave function at the beginning of each step and thus the normalized distribution of probability density $|\Psi_n(0)|^2$ is determined.

Now the effective life time of oxide trapped charge is,

$$\tau_{eff} = \frac{\sum_{n=1}^{N} \tau_n |\Psi_n(0)|^2 e^{\frac{-T}{\tau_n}}}{\sum_{n=1}^{N} |\Psi_n(0)|^2 e^{\frac{-T}{\tau_n}}} \tag{4.43}$$

where,

N = total number of steps

T = delay time after switching

The results obtained by equation (4.43) is shown in Fig. 4-7. In this case, the oxide layer width is considered as 100 A° and total number of steps is 50. The results shows that the effective life time τ_{eff} increases with the increase of time after switching and becomes constant after some time. It happens because near the switching moment almost of the oxide trapped charge tunnel out from the oxide layer and the amount of

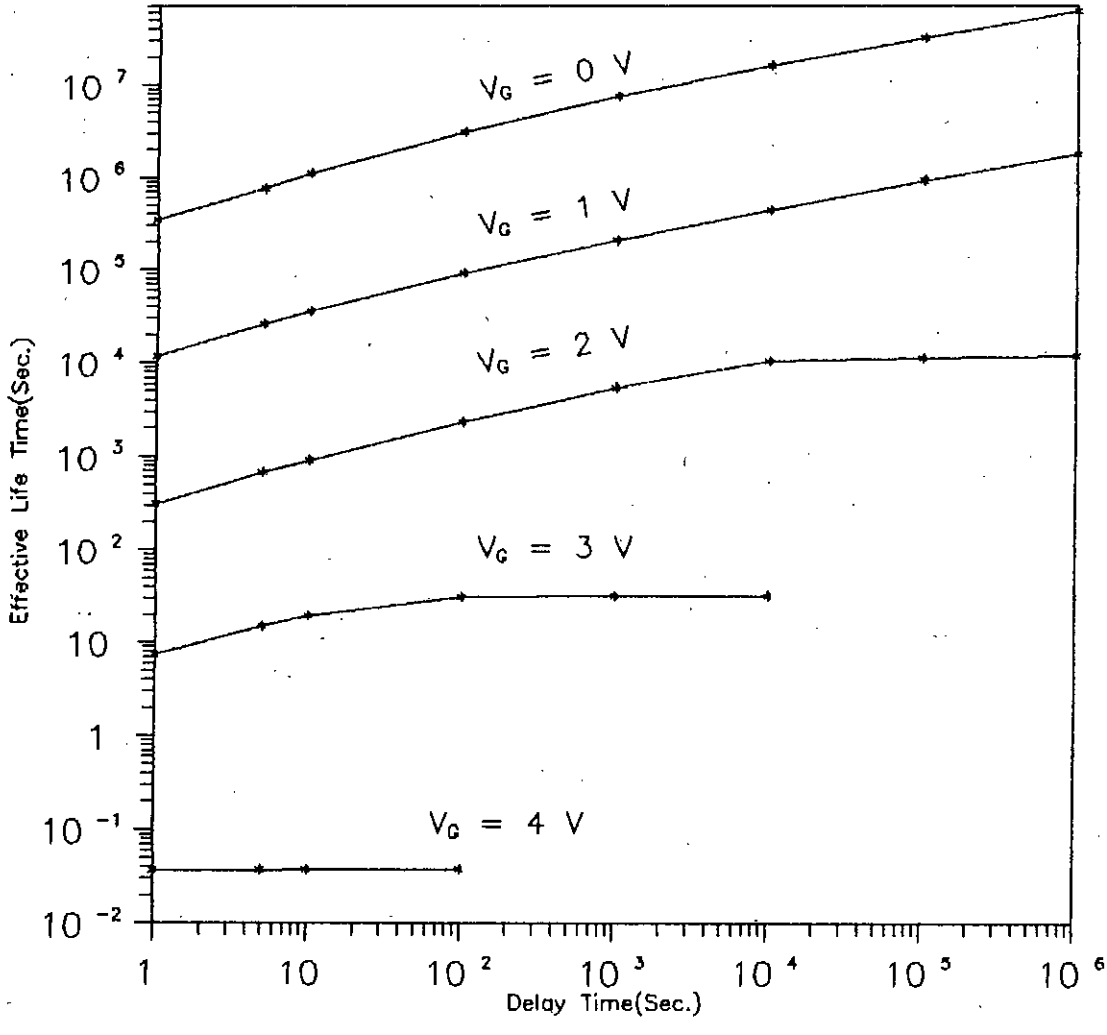


Fig. 4.7 Time dependence of the effective life time of oxide trapped charge. The initially applied gate voltage is 6 volt and the marked V_G in the figure is the gate voltage after switching.

charghe associated with tunneling discharge decreases with the time. Effective life time becomes constant due to permanent trapping of some charge carriers. τ_{eff} also increases with the decrease of applied gate voltage after switching. It happens due to a slower detrapping under reduced gate voltage.

Very few reports dealing with theoritical analysis of relaxation characteristics of trapped charges are available in the literature[5,9]. Lundstrom and Svensson [9] derived the model to calculate life time of oxide trapped charge considering the charged trap center as a three dimensional delta function without any definite width of oxide layer. According to his model the life time of 10^{-9}s, 10^{-4}s and 10s were obtained for a trap center situated at a distance of 10A°, 20A° and 30A° respectively. Trap depth, trap distribution and electric fields, however, were not clearly mentioned in this report.[9] Brox and Weber[5] calculated the tunneling time constant of 10^{-7}s, 5s and 10^{4}s for holes trapped at a distance of 10A°, 20A° and 25A° respectively. In the calculation, they used a model developed by Manzini and Modelli (Ref. 6 of [5]) which is based on WKB approximation. The results mentioned above were calculated for trap depth of 2.5 eV under no external bias. In this work, we developed a simple model for tunneling time constant of trapped electron considering the charged trap center as a one dimensional delta function. Using this model we calculated a time constant of $2x10^{-11}$s, 10^{-4}s and 5s for trap center situated at 10A°, 20A° and 30A° respectively for a trap depth of 2.95 eV under no external bias. A comparative study of the results mentioned above reveal a reasonable agreement despite variations of different parameters. The model developed in this work is based on quantum mechanical wave impedance concept which is a simple and effective tool to study the relaxation phenomena of trapped charges in the insulating layer of an MOS structure.

4.4 Discussion :

The life time of oxide trapped charge not only limits the operation speed of MOS structure but also determines the transport mechanism operating in a particular device. In this chapter, first an analytical model is developed to determine the life time of oxide trapped charge which makes use of the stationary state wave function and then this model is extended to determine the effective life time of oxide trapped charge when the gate voltage is switched from one to another lower value which is less than the initial applied voltage. In the later case, the concept of direct tunneling from semiconductor (or metal) to oxide is used. The obtained life time shows reasonable agreement with Lundstrom and Svensson's [9] result and also with the result obtained by the equation which is developed by Manzini and Modelli [5].

CHAPTER-5

CONCLUSIONS

5.1 Conclusions :

The basic MOS structure and it's operations are discussed. The creation of oxide trapped charge and the effects of interface trapped charge on the ideal MOS characteristics are also discussed. The general physics of resonant tunneling is discussed. In this work, the quantum mechanical wave impedance concept is used for reformulating the tunneling theory. A good qualitative agreement is obtained with previous models. The tunneling of electrons between the conduction band of a semiconductor (metal) and a trap center in the insulator for an MOS structure is discussed.

An analytical model is developed for the life time of oxide trapped charge by using stationary state wave function. This model is developed by exploiting a similarity with the double barrier resonant tunneling structure (DBRT). It is developed under no applied electric field and by considering the tunneling probability of oxide trapped charge through both the metal-oxide and semiconductor-oxide interface. In previous works, the life time of trapped charge is calculated considering tunneling discharge through one interface only [5,9]. Here, the trap wave function is considered as an one dimensional delta function. The calculated results show reasonable agreement with the results reported by others[5,9]. Assumption of an one dimensional delta function rather than a three

dimensional delta function as was assumed by Lundstrom and Svensson, has made the analysis quite simple with considerable accuracy.

A simple analytical formulation for the effective life time of oxide trapped charge is derived under different gate voltages during relaxation and at different time intervals after switching. The effective life time makes use of the probability density distribution corresponding to the trapped electron due to the initial applied gate voltage. The results show reasonable agreement with the physical concept. These results can well be used to understand and estimate the qualitative nature of hot carrier induced degradation and oxide reliability of thin film MOS devices.

5.2 Suggestions :

In this work, the analysis has been carried out considering discrete trap levels at various distances from the interface and neglecting interaction between traps. One dimensional delta function is taken as trap wave function which is certainly not unique to study the relaxation characteristics of oxide trapped charge in an MOS structure. Consideration of a practical trap distribution with hopping charge transport (trap assisted tunneling) certainly come up with a further extension of this work. Moreover, calculation of threshold voltage recovery using a practical trap distribution function (both spatial and energy) and comparison of the calculated results with reported experimental data will be a nice work.

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