ANALYTICAL MODEL OF SURFACE POTENTIAL AND THRESHOLD VOLTAGE OF BIAXIAL STRAINED SILICON NMOSFET INCLUDING QME

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ABSTRACT

In this paper physics based analytical model for threshold voltage of nanoscale biaxial strained nMOSFET has been presented. The maximum depletion depth and surface potential in biaxial strained–Si nMOSFET is determined, taking into account both the quantum mechanical effects (QME) and effects of strain in inversion charge sheet. The results show that a significant decrease in threshold voltage occurs with the increase in the germanium content in the silicon germanium layer. The results have been compared with the published data and the effect of variation of channel doping concentration has been examined.

KEYWORDS: *Mobility, QME, MOSFET, strained-silicon (sS), biaxial, threshold voltage, surface potential, depletion depth.*

I. INTRODUCTION

Strained silicon technology has enhanced the performance of planar MOSFET structure, which is reaching its scaling limits. To extend Moore's law for nanoscale MOSFET, new materials and new innovations on MOSFET structures are being implemented and explored by the researchers. At 130nm and down to 32nm the semiconductor industry has used strained silicon technology to increase the carrier mobility in the active region of the MOSFET by introducing strain in the silicon channel [1]. Strain can be applied as either biaxial or uniaxial. To develop a physical insight and understand the characteristics of strained silicon MOSFET, its model equations are required. The modeling of electrical characteristics has been carried out by various researches [7]. The nanoscale planar MOSFET structure are affected by SCEs and QMEs which are included in [3] and to explain the biaxial physical phenomenon the model equations for stained silicon MOSFET must include the combined effect of strain, SCE, and QMEs [10, 13]. Inversion charge sheet is the one of the important parameters which helps in good understanding of the study of threshold voltage of a MOSFETs. The first step in this direction is to understand the inversion charge sheet in the channel in a strong inversion region, by modeling the maximum depletion depth, surface potential and hence the threshold voltage of strained silicon biaxial nMOSFET. Therefore, in this paper, a biaxial nMOSFET as shown in figure 1(i) has been studied.

The paper is organized as, section I gives the QMEs in strained silicon MOSFET, section II gives the details of QMEs in strained silicon MOSFET, section III gives the analytical modeling of threshold voltage in strained silicon MOSFET. Discussion of results and conclusion is given in section IV.

II. QMEs IN STRAINED SILICON MOSFET

A layer crystalline SiGe alloy, which has a higher lattice constant then Si, is grown over the substrate. Over which an epitaxial layer Si is grown, taking the same crystallographic orientation as the SiGe layer.

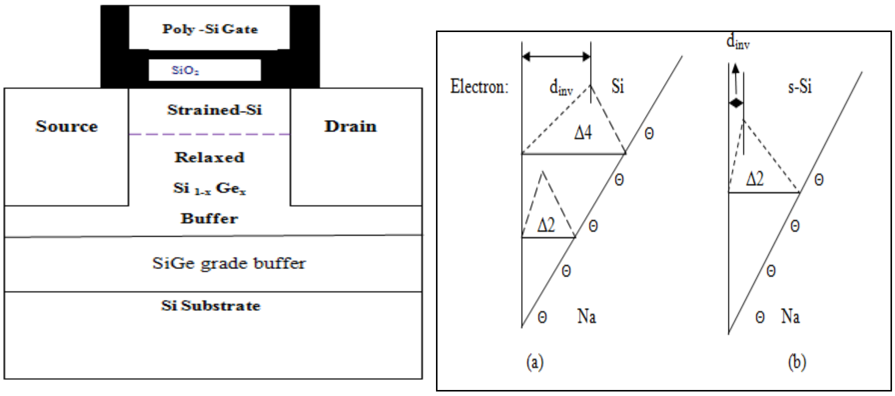

Figure 1(i) Device structure of biaxial strained-Silicon nMOSFET [3] (ii) Schematic diagram of the interoperation for the effect of biaxial tensile strain on inversion charge sheet [5]

The strain is developed in the upper layer due to the mismatch of the lattice constants of two layers causing a strained silicon layer. This process yields high speeds without scaling down the devices. The strain alters the band structure in the channel, this provides lower effective mass, suppresses intervalley scattering and results in enhancement of carrier mobility and the device on current. Energy quantization in nanoscale MOSFET causes shifts in the inversion charge sheet which influences the surface potential as well as threshold voltage of MOSFETs. Each energy level of silicon is composed of six equal energy states in three dimensions. The conduction band splitting due to QME has been shown in figure 1(ii). When biaxial stress is applied, the Δ2 states and Δ4 states are split up into lower and higher energy states respectively. This band alteration gives an alternate lower energy site for electrons to reside i.e. Δ2. The difference in the energy levels causes repopulation of the electrons in the lower energy states Δ2. The effective mass of electrons in the Δ2 valley is lesser than the Δ2. The effective mass of electrons in lower energy states is reduced from $0.33m_o$ in unstrained silicon to $0.19m_o$ in strained silicon structures as shown in figure 2 [5]. Due to this, the electron mobility increases. The biaxial tensile strain enhances electron mobility due to Δ2 valley population enhancement and the resulting decrease in the effective mass [11]. Biaxial tensile strain increases the occupancy of electrons in Δ2 valleys which exhibit much thinner layer than electrons in Δ4 valley and thus Δ4 decreases the distance between electrons and electron scattering centre located at the SiO2/Si interface.

III. ANALYTICAL MODELING APPROACH

The classical definition of for determination of depletion depth as well as surface potential of the biaxial strained–Si nMOSFET, i.e. inversion layer electron concentration at the interface becomes equal to bulk hole concentration. The conduction band (in nMOSFET) , the strain induces a subband energy splitting $\Delta E \approx 0.67$meV for each 0.10 increment in x, between the perpendicular Δ2 and parallel Δ4 sub-band [8] . The 2-D energy splitting for strained Si nMOSFET is shown in figure 2. Inversion charges on the sub-band energy followed by two dimensional distribution and total inversion charge Q_{inv} is divided into two parts Here Q_{inv1} and Q_{inv2} correspond to the inversion charge sheet density associated with valley one and valley two, respectively [4].

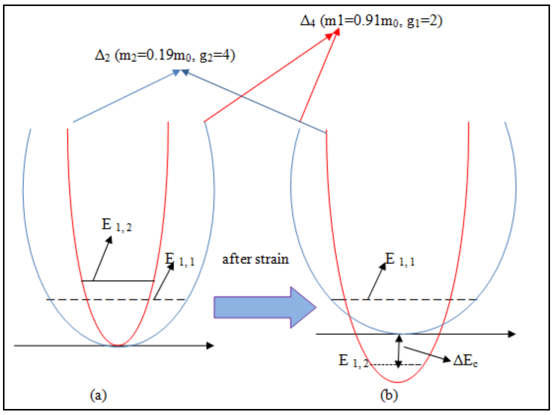

Figure 2: 2-D Energy quantization model for strained –Si model and interoperation of strain effect

$$Q_{inv} = Q_{inv1} + Q_{inv2} \quad (1)$$

$E_{1,1}$ and $E_{1,2}$ are first energy level for valley-1 and valley-2 respectively. Quantization effect splits continuous energy band into discrete energy level and applied strain causes shift in E_{12} valley by an amount $Ec \approx 0.63x$ (eV). The shifted energy band is given by $E'_{12} = -\Delta E_C + E_{1,2}$. The modified energy level due to QME in strained silicon can be written as

$$E'_{1,2} - q\phi_S^{sS} + q\phi_B^{sS} + \frac{E_g^{sS}}{2} = -kT\log\left(\frac{Q_{inv,2}}{qN_{C2}}\right) \quad (2)$$

Here ϕSsS, ϕBsS, EgsS are surface potential, bulk potential and energy band gap for strained silicon MOSFETs respectively. All these parameters are function of germanium mole fraction x. The inversion charge Q inv2 is given by

$$Q_{inv2} = qN_{c2}\exp\left(\frac{E_F - E_{12}}{kT}\right) \quad (3)$$

Here N_{c2} is the 2-D state charge sheet density and g2 is degeneracy of the energy sub-band valley-2 of lower mass and it is defined as

$$N_{c2} = \frac{kTg_2 m_{d2}^{*}}{\pi\hbar^2}, \quad (4)$$

Using (3) and (4), in (2) gives

$$-\Delta E_C + E_{1,2} - q\phi_B^{sS} + q\phi_B^{sS} + \frac{E_g^{sS}}{2} = -kT\log\left(\frac{Q_{inv,2}}{qN_{C2}}\right) \quad (5)$$

The surface potential for biaxial strained silicon nMOSFET is defined as,

$$\phi_S^{sS} = \frac{qN_a d_{cl}^{sS^2}}{2\epsilon_{si}}, \quad (6)$$

dsScl is the depletion depth in classical model. Since the differ between the classical depletion and quantum mechanical depletion is small compared with the depletion depth itself and combining both quantum mechanical concept as well as strain and assuming that

$$\frac{d_{qm}^{sS} - d_{cl}^{sS}}{d_{cl}^{sS}} \leq 1, \quad (7)$$

Using (9) in (7), we obtain

$$d_{cl}^{sS} \Leftrightarrow d_{qm}^{sS}, \quad (8)$$

By using (7) and (8), (5) can be rewritten as

$$-\Delta E_C + \frac{9q^2 N_a d_{qm}^{sS}}{4\epsilon_{Si}\alpha_z} - \frac{q^2 N_a d_{cl}^{sS^2}}{2\epsilon_{Si}} + q\phi_B^{sS} + \frac{E_g^{sS}}{2} = -kT\log\left(\frac{Q_{inv,2}}{qN_{C2}}\right) \quad (9)$$

$$d_{qm}^{sS\ 2} - \frac{4.5}{\alpha_z} d_{qm}^{sS} + C = 0 \quad (10)$$

Here C is becomes equal to

$$C = -\frac{2L_D^2}{kT}\left[-\Delta E_c + q\phi_B^{sS} + \frac{E_g^{sS}}{2} + kT\log\left(\frac{N_a}{N_{C2}}\right)\right] \quad (11)$$

N_a is doping concentration and total inversion charge sheet shifted due to both combining QME and strain effect in a MOSFET can be determine by solving by above (12) which shows observe that inversion charge sheet is function of germanium mole fraction. Equation 12 d_{qm}^{sS} is the shifted inversion sheet due to QME in Biaxial strained-silicon MOSFET. In Biaxial strained silicon MOSFET, Si1$_{-x}$Ge$_x$ layer and strained-silicon layer is much thinner and also assume that total depletion width in silicon substrate then maximum depletion width W_{dm}^{sS} is defined as

$$W_{dm}^{sS} = d_{qm}^{sS} + t_{Si} + t_{SiGe}. \tag{12}$$

Maximum depletion depth at the onset of strong inversion takes place.

$$\Phi_s^{sS} = \frac{W_{dm}^2 q N_a}{2\epsilon_{Si}} \tag{13}$$

Bulk potential for strained silicon MOSFET is defined as

$$\Phi_B^{sS} = \frac{kT}{q} log\left(\frac{N_a}{n_i^{sS}}\right). \tag{14}$$

n_i^{sS} is the intrinsic carrier concentration for strained silicon. Due to quantum mechanical effect surface potential is slightly increased. Increased surface potential after taking QM effect can be estimated and modified surface potential is written as

$$\Phi_{s,md}^{sS} = \Phi_s^{sS} + \Delta\Phi_{sS}^{QM}. \tag{15}$$

Quantum mechanical effect also changes flat band potential corrected or modified is presented by

$$V_{FB}^{md} = V_{FB} + qN_a\left(\frac{d_m'}{2\varepsilon_{Si}} + \frac{t_{ox}^{md}}{\varepsilon_{ox}}\right), \tag{16}$$

ϵ_{ox} and ϵ_{Si} the permittivity of SiO_2 and Si. The threshold voltage for strained-Si channel MOSFET can be expressed as

$$V_{th}^{ss} = V_{FB}^{md} + \Phi_{s,md}^{sS} + \Phi_{ox}^{md} \tag{17}$$

Oxide potential is the second important factor which also plays a significant role in threshold calculation. The oxide potential can be calculated by following relations

$$\Phi_{ox}^{sS} = \Upsilon\left(\sqrt{\Phi_s^{sS}}\right),$$

where γ the body coefficient. C_{ox} being the oxide capacitance per unit area in the inversion, and ϵ_{Si} is the average permittivity of the strained–Si and Si$_{1-x}$Ge$_x$ layers. As mentioned in section 2, the physical oxide thickness is slightly increased, when considering QM effect , named effective oxide thickness and modified expression for effective oxide thickness is written as [5, 6].

$$t_{ox}^{md} = t_{ox} + \frac{\epsilon_{ox}}{\epsilon_{Si}} d_m',$$

d'_m is changed in depletion depth due QME. As result Υ_{md} is the body effect coefficient which also changed the modified expression is

$$\Upsilon_{md} = \frac{\sqrt{2qN_a\varepsilon_{Si}}}{C_{ox}^{md}}$$

$$C_{ox}^{md} = \frac{\varepsilon_{ox}}{t_{ox}^{md}},$$

being the oxide capacitance per unit area in inversion, and ε_s is the average permittivity of the strained- silicon and Si$_{1-x}$Ge$_x$ layer [7,12].

IV. RESULTS AND DISCUSSION

In the modeled threshold voltage of strained –Si MOSFETs, the value of in the range 0.05 to 0.4 is taken, beyond which strain is more likely to be relaxed [11].

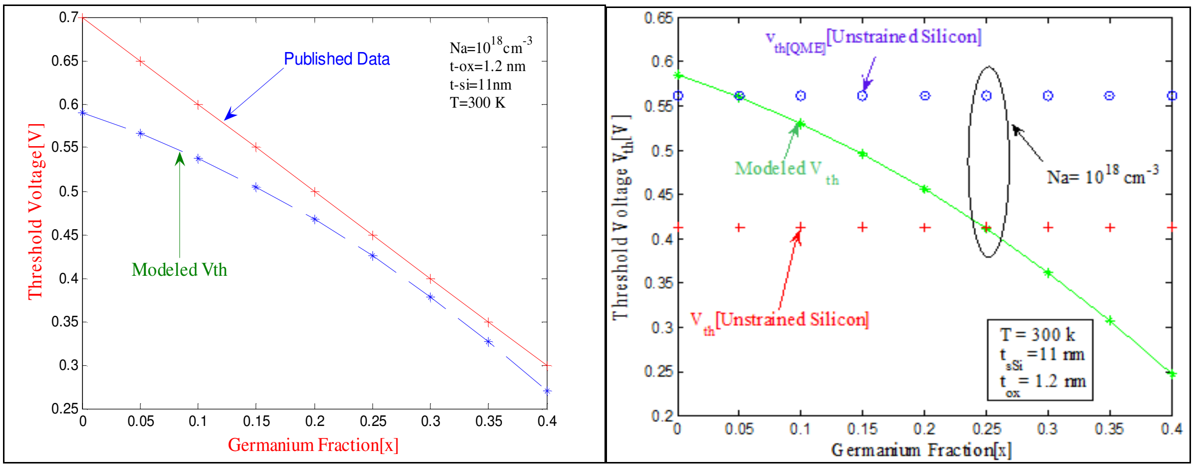

Figure 3(i): Variation of threshold voltage for various Ge mole fraction and bench marking with publish data. **(ii):** Comparison of threshold voltage in unstrained, unstrained with QME and strained Silicon MOSFET.

Figure 3(i) displays the variation of threshold voltage against Ge mole fraction x and bench marking with published data. It is observed that the results obtained from analytical model are in close agreement with published data A comparison of results from proposed model with the unstrained without QM effect and with QM effect against Ge mole fraction x is done in figure 3(ii). It is observed the threshold voltage decreases for a higher value of x and at the same doping concentration in strained-Si MOSFET. Threshold voltage is less than that of unstrained silicon MOSFET. Reason for this is, as x increases, the conduction and valance band offset also rise [3,5], thereby decreasing the value surface potential ($\phi^{sS}{}_{S}$), the drop in $\phi^{sS}{}_{S}$ causes a decrease in threshold voltage. Therefore, strained-Si technique minimizes QMEs and by increasing Ge content in SiGe effect of increase in threshold voltage due to QMEs at nanoscale in MOSFET can be mitigated.

Figure 4 (i) and (ii) show the variation of maximum depletion depth, W_{dm} against Ge mole fraction, x. A comparison of proposed analytical results of unstrained with stained Si MOSFET with x, for channels doping concentration for range of 10^{16} to 10^{18}[cm^{-3}] has been done. It is observed W_{dm} decreases with increase in N_a and also with increase in value of x. W_{dm} plays a significant role for determination of surface potential and hence the threshold voltage.

Figure 5 shows variation of surface potential against channel doping concentration. It can be observed that energy quantization causes slight increase in the the surface potential in planar MOSFET and when biaxial stress is applied in nanoscale MOSFET, bandgap narrowing occurs. Smaller bandgap causes increases in intrinsic concentration of strained silicon. Thus biaxial strain reduces the inversion charge sheet shift and surface potential for biaxial strained nMOSFET reduced at the same doping concentration.

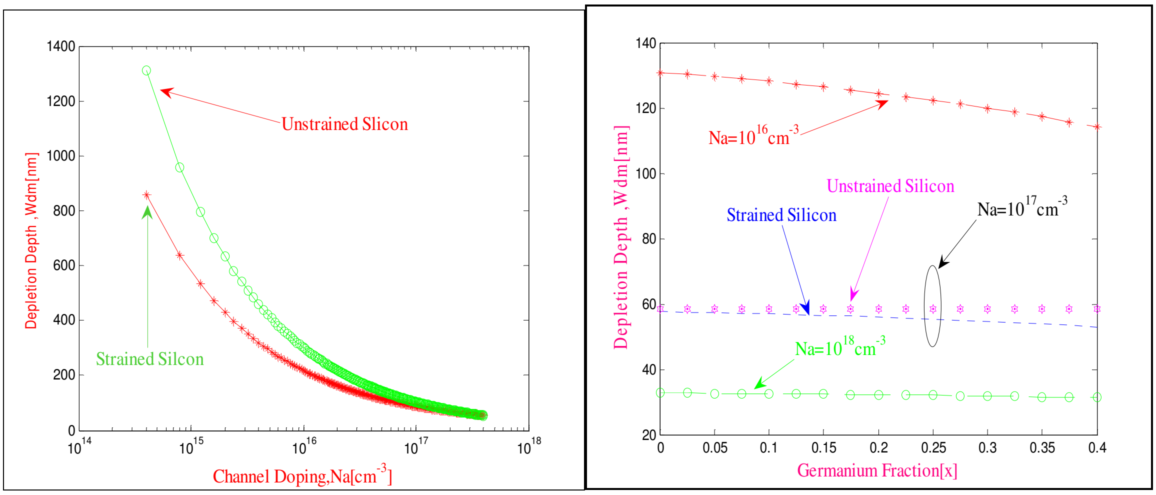

Figure 4(i) Variation of depletion depth with doping concentration. (ii)Variation of depletion depth with Ge mole fraction x.

V. CONCLUSIONS

An analytical model for determination of surface potential, depletion depth and threshold voltage of biaxial strained –Si nMOSFETs including quantum mechanical effect has been presented. Quantum mechanical effect is influences the surface potential as well as threshold voltage for nanoscale MOSFET. The modeling result shows that quantum mechanical effect that causes increase in threshold voltage of nanoscale MOSFET can be mitigated by introduction of strain. Threshold voltage, which is dependent on surface potential can be controlled by variation of various processes in n-MOSFET strained-Si MOSFET fabrication. The threshold model developed here can be used to develop the I-V characteristics of strained silicon MOSFET and can help in more clear understanding of device performance.

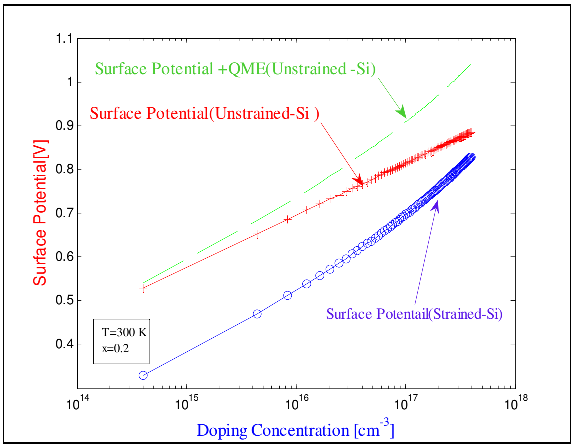

Figure 5 Dependence of surface potential on channel doping concentration (N_a)

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