A PHYSICS BASED MODEL OF INVERSION CHARGE SHEET (ICS) FOR NANOSCALE BIAXIAL STRAINED – SILICON NMOSFET INCLUDING QUANTUM MECHANICAL EFFECT (QME)

Shiromani Balmukund Rahi[1], and Garima Joshi[2]
Assistant Professor (ECE), SIIT, Gorakhpur, Uttar Pradesh, India
Assistant Professor (ECE), Deptt, UIET, Panjab University Chandigrah, India

ABSTRACT

In this paper, a physics based model of inversion charge sheet of nanoscale NMOSFETs has been presented. The model is formulated for nanoscale biaxial strained silicon NMOSFET including quantum mechanical effect (QME). The QME is splitting of conduction band due to very thin oxide (t_{ox}) and very large doping concentration of ultra small geometry of MOSFET. The QME shift the inversion charge sheet into subtracts. To overcome this problem strain technique is used because this shift is very small but this is effect causes increase in the surface potential as well as threshold voltage of nanoscale MOSFET. The modeling approach is to develop the model for inversion charge sheet after combining both QME and strain effect for biaxial strained silicon NMOSFET .The result shows a significant decrease in the inversion charge sheet of increasing the germanium mole fraction (%x) in silicon germanium heterostrusture virtual substrate. The presented result has been good agreement with published data. The result shows that QME is minimized by using strain technique in biaxial strained silicon NMOSFET. Presented result is valid for large range of doping concentration as well as mole fraction.

KEYWORDS: *MOSFET, QME, strained- Silicon(s-Si), biaxial, uniaxial, ICS, germanium mole fraction, SLSI.*

I. INTRODUCTION

Strained silicon technology enhances the channel mobility 2 to 3 times larger than classical MOSFET. Strained–Si MOSFET improves the performance of Complementary-Metal-Oxide Semiconductor (CMOS) for next generation VLSI [1, 2]. The applied strain improves the performance of MOSFET by increasing the mobility as well as reducing the surface potential which in turn decreases threshold voltage even for higher doping concentration. The applied strain causes splitting of conduction into lower valley and heavier valley mass .The mobility enhancement is due to decrease in the effective mass in Δ2 valley and scattering of electrons. The change in effective mass also lowers the eign energies which enhances the electron occupancy in the ground state [1].

Strain can be applied either biaxial or uniaxial. Typically, biaxial tensile stress is introduced via a thin epitaxial silicon channel grown on relaxed $Si_{1-x}Ge_x$ substrate [3]. Inversion charge sheet is the one of the important parameters which helps in good understanding in the study of threshold voltage for MOSFETs. This paper presents the analysis for inversion charge sheet shift of biaxial strained silicon nMOSFET combining the Quantum mechanical effect (QME) and the effect of strain.

The paper organized as, section I give the overview of strained silicon technology and strained silicon MOSFET, section II gives the details of QMEs in strained silicon MOSFET. Modeling and formulation of inversion charge sheet are discussed in section III. Results and discussions are given in section IV. In section V, conclusion and future work are presented.

II. STRAIN AND QME

According to the semi classical sheet model, the inversion charge carriers are treated as a sheet charge at the Si-gate oxide interface. The inversion sheet helps to analysis in the threshold voltage. Present day MOSFET dimensions are in nanometers. Shrinking of device dimensions below a certain limits gives rise to undesirable effects known as short channel effects (SCEs). To overcome these undesirable effects there is need of new device material or dimensions such as strained–Si channel MOSFETs [4]. To improve device performance the high doping concentrations of substrate with very thin oxide thickness is required. Due to higher subtract doping concentration and thinner gate oxide in modern MOSFETs, the electric field near the Si/SiO_2 interface is strong enough causes energies quantization. Energy quantization causes shifts in the inversion charge sheet which influences the surface potential as well as threshold voltage of the MOSFETs. Therefore an accurate modeling for threshold voltage, there is need for good understanding for inversion charge sheet for nanoscale MOSFETs [5].

On the other hand, biaxial strained-Si technique also causes the splitting of conduction band (NMOSFETs) into lower valley and higher valley masses. One important issues is the charge of subband energies of electrons of bulk Si without strain, the energy of two fold–valley (Δ2) (light-electron) band is lower than that of four fold valley (Δ4) (heavy-electron) band. Although tensile strain enlarges the energy splitting between Δ2 and Δ4 bands within the amount of strain the subband energies of Δ2 (light-electron) are still lower than that of the (heavy-electron) Δ4 band. One important issue is the inversion layers in Δ2 are smaller than heavy electron in Δ4 valley [2].

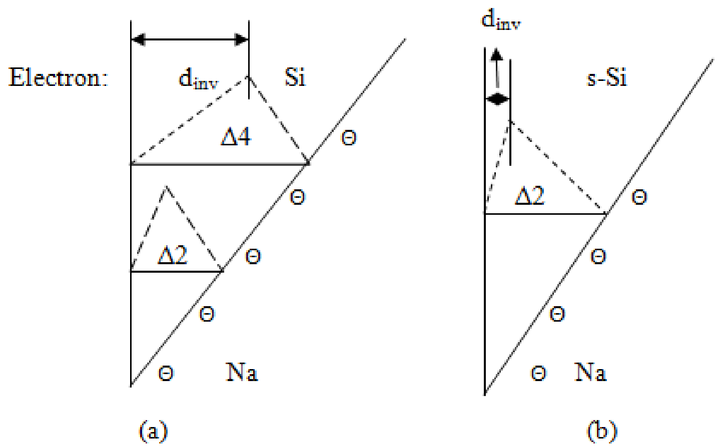

Figure 1: Schematic diagram of the interoperation for the effect of biaxial tensile strain on inversion Charge Sheet (ISC) [11, 13].

The Biaxial strain enhances electron mobility due to Δ2 valley population enhancement and the resulting decrease in the effective mass. Mean while biaxial tensile strain increases the occupancy of electros 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 Si/SiO_2 interface as shown in Fig-1. Fig.2 shows the schematic diagram of biaxial strain silicon NMOSFET considered in this paper.

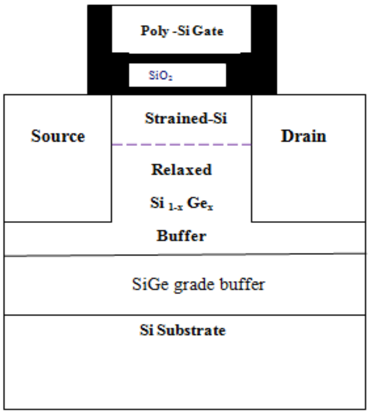

Figure 2: Device structure of biaxial strained-Silicon NMOSFET [11]

III. Modeling and Formulation of Inversion Charge Sheet

The basic approach for determine the inversion charge sheet is the classical MOSFET concept i.e. inversion layer electron concentration at the interface becomes equal to bulk hole concentration. In biaxial strained silicon NMOSFET, the applied strain caused the splitting of conduction band into lower valley and heavier valley masses, the sub band energy splitting ΔEs ≈0.67meV for each 0.10 increment in x, where x is Ge mole fraction, between the perpendicular Δ2 and parallel Δ4 sub band [7].Thus increase in the overall splitting that associated with quantization (Fig. 3). The applied strain causes decrease in conduction band of NMOSFET, resulting increase in conduction band offset, which is determined by relation.

$$\Delta E_{g(sSi)} = 0.4.x(eV) \tag{1}$$

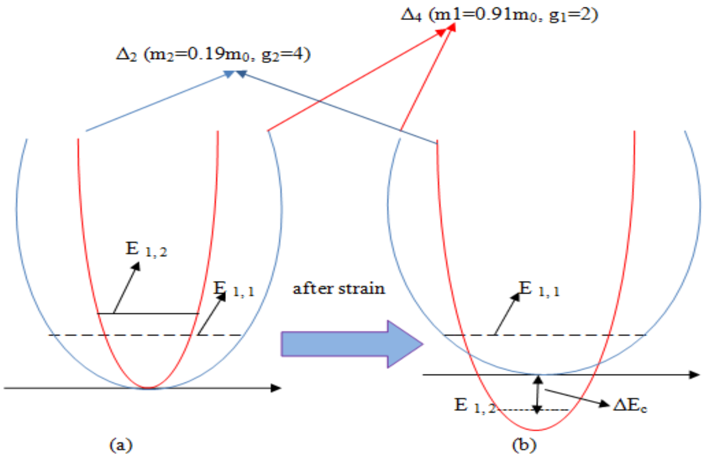

Figure 3: 2-D Energy quantization model for strained–Si model and interoperation of strain effect [11].

It is considered that the MOSFETs are uniformly doped p- type substrate. The electrons presents in this well occupy a setoff energy sub-bands, which distribute energy and wave-function should follow the combination Schrödinger's equation and Poisson's. Inversion charge distribution in MOSFET in subband energy followed by two dimensional distributions and total inversion charge Qinv is divided into two parts [8], which is denoted by Qinv, 1 and Qinv,2,here Qinv, 1 and Qinv,2 are the inversion charge distribution for valley-1and valley-2 respectively

$$Q_{inv} = Q_{inv,\,1} + Q_{inv,\,2} \tag{2}$$

In Fig-3 E1, 1, E 1,2 first energy level for valley-1 and valley-2, respectively. Quantum mechanical effect splits continuous energy of conduction the into discrete energy level and applied strain causes shift in energy $E_{1,2}$ by an amount ΔEc≈0.63x (eV).i.e. The modified energy label $E_{1,2}$, is determined by Eq. (3).

$$E'_{1,2} = -\Delta E_C + E_{1,2} \quad (3)$$

The quantized energy level $E_{1,2}$ can be written as

$$E_{1,2} = \frac{3h^2\alpha_2}{m_2} \quad (4)$$

Here α2 is varitional parameter and related with wave functions and m2 is effective mass for valley-2[8]. h is Planks constant. For strained silicon MOSFET modified energy level including QME can be written as

$$-\Delta E_c + E_{1,2} - q\phi_S^{sS} + q\phi_B^{sS} + \frac{E_g^{sS}}{2} = -kTlog\left(\frac{Q_{inv,2}}{qN_{c2}}\right) \quad (5)$$

Here ϕ_{ssS}, ϕ_{BsS}, Eg_{sS} are surface potential, bulk potential and energy band gap for strained silicon MOSFETs respectively, all these parameters are function of germanium mole fraction. $Q_{inv,2}$ written as

$$Q_{inv,2} = qN_{c2}exp\left(\frac{E_F - E_{1,2}}{kT}\right) \quad (6)$$

Here Nc2 is the 2-D state charge sheet density for electron which is defined as

$$N_{c2} = \frac{kTg_2m_{d2}^*}{\pi\hbar^2} \quad (7)$$

g2 is degeneracy of the energy subband valley-2 of lower mass. Eq. 5can also be re-written as

$$-\Delta E_c + E_{1,2} - q\phi_S^{sS} + q\phi_B^{sS} + \frac{E_g^{sS}}{2} = -kTlog\left(\frac{Q_{inv,2}}{qN_{c2}}\right) \quad (8)$$

By using classical concept, surface potential for biaxial strained silicon nMOSFET is defined as

$$\phi_S^{sS} = \frac{qN_a d_{cl[sS]}^2}{2\varepsilon_{Si}} \quad (9)$$

Here dcl[sS] is the depletion depth in classical model for strained silicon MOSFET. In quantum mechanical, depletion depth is slightly larger than classical and its difference is very small compared with the depletion itself [8].Similar concept is used for strained silicon. Here suffix sS strands for strained silicon, i.e. Channel Doping Concentration Na [cm^{-3}], d_{inv} [nm] Unstrained Strained

$$\frac{d_{qm}^{sS} - d_{cl}^{sS}}{d_{cl}^{sS}} \leq 1 \quad (10)$$

or

$$d_{cl}^{sS} \Leftrightarrow d_{qm}^{sS} \quad (11)$$

Using Eq. (9) and Eq. (11), Eq. (8) can rewritten as

$$-\Delta E_c + \frac{9q^2N_a d_{qm}^{sS}}{4\varepsilon_{Si}\alpha_2} - \frac{q^2N_a d_{qm\,[sS]}^2}{2\varepsilon_{Si}} + q\phi_B^{sS} + \frac{E_g^{sS}}{2} = -kTlog\left(\frac{Q_{inv,2}}{qN_{c2}}\right) \quad ....(12)$$

$$d_{qm}^{sS} = \frac{1}{2}\left(\frac{4.5}{\alpha_2} + \sqrt{\left(\frac{4.5}{\alpha_2}\right)^2 - 4C}\right) \quad (13)$$

Here C is user variable and defined as

$$C = -\frac{2L_D^2}{kT}\left[-\Delta E_c + q\phi_B^{sS} + \frac{E_g^{sS}}{2} + kTlog\left(\frac{N_a}{N_{c2}}\right)\right] \quad .....(14)$$

L_D is Deby length and Na is doping concentration. Total inversion charge shift is determined by using Eq .13. This equation present that inversion charge shift in biaxial strained silicon nMOSFET is function of germanium mole fraction and doping concentration.

IV. RESULTS AND DISCUSSIONS

When biaxial stress is applied, bandgap narrowing occurs. Smaller bandgap causes increases in intrinsic concentration of strained silicon. This biaxial strain reduces the inversion charge sheet shift reduces after including quantum mechanical, resulting that biaxial strain technique reduces the quantum mechanical effect. This is evident from fig. 4.

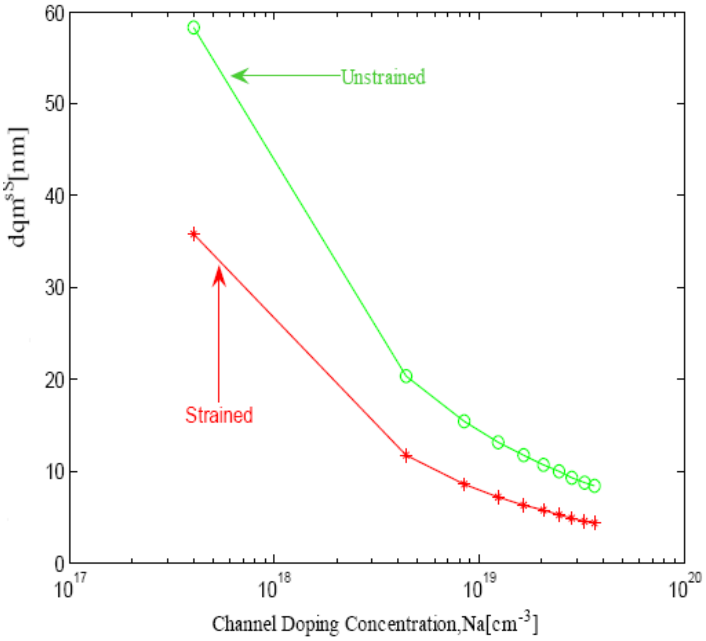

Figure 4: Interoperation of unstrained and strained silicon inversion charge sheet for nMOSFET with various doping concentration.

It is evident that at the process level of MOSFET, by introduction of strain technique reduces the quantum mechanical effect for various level of germanium mole fraction. Figure-5 represent that in biaxial strained technique quantum mechanical effect is less effect in comparison with unstrained silicon at the same doping concentration.

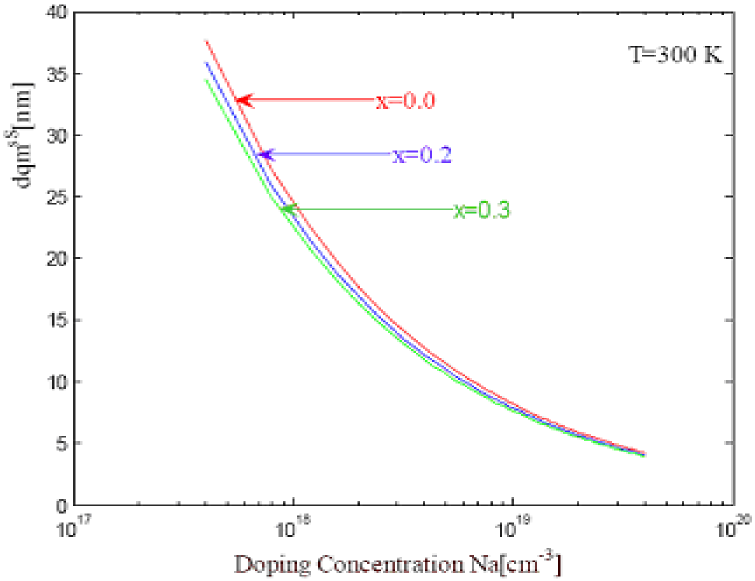

Figure.5: Inversion charge shift variation against germanium mole fraction with various doping concentration

Comparison of inversion charge shift for x=0.0, 0.2 and 0.3. From fig.5, it is clear that at the process label in MOSFET, quantum mechanical effect can be minimized by using appropriate germanium mole fraction. But higher value of germanium mole fraction causes surface roughness. The surface roughness particularly at the $Si/Si_{1-x}Ge_x$ interface for Si layer thickness plays an important in enhancing the threshold voltage [3].

V. CONCLUSION AND FUTURE WORK

In conclusion a physics based model of inversion charge sheet for biaxial strained silicon NMOSFET including quantum mechanical effect has been presented. In nanoscale MOSFET QME is more effective , which influence the inversion charge sheet , surface potential[6] as well as threshold voltage[11,12] .The modeled result indicate that the QME shift the peak of inversion charge sheet into strained silicon(or bulk) and by using strain technique QME effect is mitigated. Since threshold voltage is function of inversion charge sheet can minimized by applying strain in biaxial strained silicon NNOSFET. This is best agreement of published result [6,11,12,13].

The inversion charge sheet model developed here can be used to develop the model for surface potential as well threshold voltage for nanoscale MOSFET which can help in more clear understanding of I-V characteristics of devices for next generation CMOS technology for (super large scale integration)SLSI .

ACKNOWLEDGEMENTS

The author who wishes to acknowledge the director, Suyash Institute of Information Technology, Gorakhpur, Uttar Pradesh, India, who provide me opportunity for writing this paper.

REFERENCES

[1] M. Jagadesh Kumar, Vivek Venkatraman and Susheel Nawal 2007 Analytical Drain Current Model of Nanoscale Strained- Si/SiGe MOSFETs for Analog Circuit Simulation Proc. IEEE 20th International Conference on VLSI Design.

[2] Yutao Ma, Zhijian Li, Litian Liu and Z.Yu May 2000 MOS Structure Threshold Voltage Model Rigorously Considering Quantum Mechanical Effect Proc. 22nd International Conference on Microelectronics Vol l.1 pp.14-17.

[3] Hasan M. Nayfeh, Judy L. Hoyt, Dimart and A. Antoniadis December 2004 A Physically Based Analytical Models for the Threshold Voltage of Strained–Si n-MOSFET IEEE vol.51 no.12.

[4] Scott A. Hareland, Jallepali,Wie-Kai Shih,Hailhong, Gowari L. Chindalore, Al F. Tasch and CM. Mazair Janaruy 1998 A Physically- Based Model for Quantization Effects in Hole Inversion Layers IEEE vol.45 no.1.

[5] Ning Yang, W. Kirklen Henson, John R. Hasuer and Jimmie J. Wortman July 1999 Modeling Study of Ultrathin Gate Oxides Using Direct Tnneling Current and Capacitance Voltage Measurements in MOS Devices IEEE Vol.46 no.7.

[6] Bratati Mukhopadhyay, Abhijit Biswas, PK Basu, G Eneman,P Verhenyen,E Simoen and C Clayes 2008 Modeling of Threshold Voltage and Subthreshold Slope of Strained –Si MOSFETs Including Quantum Effects Semiconductor Science Technology.

[7] G. Chindalore, S.A. Hareland S.Jallepali, A.F.Tasch, C.M. Maziar,V.K.F. Chia, and S. Smith May 1997, Experimental Determination of Threshold Voltage Shifts Due to Quantum Mechanical Effects in MOS Electron and Hole Inversion Layers IEEE Vol.18, No 5.

[8] M.A. Karim and Anisul Haque 2010 A Physically Based Accurate Model for Quantum Mechanical Correction to the Surface Potential of Nanoscale MOSFETs, IEEE, Vol. 57, No.2.

[9] Jin He, Mansun Chan, Xing Zhang and Yangquan Wang 2006 An Analytical Model to Account for Quantum-Mechanical Effects of MOSFETs Using a Parabolic Potential Well Approximation IEEE Vol.53 No.9.

[10] Vedatrayee Chakraborty, Bratati Mukhopadhyay and P. K. Basu 2009 A Compact Drift-diffusion Current Model of Strained-Si-Si1-xGex MOSFETs Proc. CODEC.

[11] "Shiromani Balmukund Rahi and Garima Joshi," Analytical Model of Surface Potential and Threshold Voltage of Biaxial Strained -Silicon NMOSFET including QME ", International Journal of Advances in Engineering &Technology (IJAET)", vol-5 issue 1pp-601-607, November 2012.

[12] Brati, Mukopadhyay, Abhijit Biswas, P.K. Basu, G. Enman Verhenyen,Simoenand C Caleys," Modeling of Threshold Voltage and Sub Tresholod Slop of Strained – Si MOSFETs including Quantum Effects ," IOP Semiconductor Science & Technology ,vol.29,pp.0268-1242, 2008.

[13] Scoot A Harelend , S Jallepail,Wei- Kai Shi, Haihongb Wang Gori L. Chainalore Al,F Tasch C.M. Maizar,, A Physically Baised Model for Quantization Effect in Inversion Layers," IEEE,vo..45, no.1, January.1998.

AUTHORS

Shiromani Balmukund Rahi received the B.Sc.(PCM) in 2002, M.Sc. (Electronics) in 2005 from DDU Gorakhpur, Uttar Pradesh and M.Tech (Microelectronis) in July 2011 from Panjab University, Chandigarh, India . Currently he is working as Assistant Professor (ECE) from Suyash Institute of Information & Technology, Gorakhpur, Uttar Pradesh, India. His current research interest in modeling of MOSFETs at Nanoscale.

Garima Joshi is M.E.(ECE)form UIET, Panjab University, Chandigarh, India. Her area of research includes modeling and simulation of Nanoscale MOSFETS. Currently, she is working as Assistant Professor (ECE) and also pursuing Ph.D from UIET, Panjab University Chandigarh. She has 10 publications in international Journels / Confrerencs proceedings.