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Mobility Models for Unstrained and Strained Silicon MOSFETS: A Review

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Abstract

In this paper, a critical review of various models for the effective mobility of charge carriers in metal oxide semiconductor field effect transistor (MOSFET) inversion layer (p and n type) has been done. Analytical, empirical and numerical models for carrier mobility have been reviewed and compared. Both strained silicon and unstrained silicon MOSFET cases have been studied. Depending upon their accuracy and simplicity, certain models have been identified to be applicable for mobility determination in strained and unstrained MOSFETs.

Keywords: Scattering; Electric field dependence; Strain; Analytical; Numerical; Empirical; Comparisons.

1 Introduction

As projected by Moore's law, the transistor density on a CMOS chip doubles approximately after every one and a half years [1]. Continuing with the Moore's law, the gate length of the MOSFET will eventually shrink to 10 nm in 2015 [2].

As the feature size of transistor decreases, the improvement in the VLSI MOSFET device models are required so that the exact behavior of deep sub-micron and nanometer scaled MOSFETs can be described with accuracy. The reduced dimensions of the device mostly affect the mobility in the inversion layer of the MOSFET. But as we scale down the MOSFET, carrier mobility decreases due to the high vertical electrical fields in the substrate. The reduction in carrier mobility is a major cause of drain current degradation. This reduces the speed of the device.

In this paper, a detailed comparative study of the different inversion layer mobility models for silicon and strained silicon MOSFET has been done. The paper is organized as follows. Section 2 deals with the numerical models. Then, section 3 gives a review of empirical models and section 4 elaborates analytical models. Section 5 compares the above mentioned models and conclusion is given in section 6.

2 Numerical Mobility Models

There are several numerical mobility models reported in the literature. Out of these, three main numerical models for the mobility of carriers in the inversion layers of MOSFET, as a function of electric field have been discussed here. In year 1979, Ken Yamaguchi [9], the effect of both parallel and perpendicular fields on the carrier mobility has been taken by using two dimensional numerical analysis of MOSFET. Variation of electron mobility with effective electric field for device parameters, substrate doping=$3.5 \times 10^{15} cm^{-3}$, effective channel length=2μm and oxide thickness=50nm is shown in figure 1. Variation of hole mobility with effective electric field is shown in figure 2. This model gives excellent agreement with experimental results. The discrepancies are only 5 percent in the current saturation region. The limitation of this model is that, the local drain gate field becomes very strong at the same time and saturation velocity intensively depends on the perpendicular electric field. The 2^{nd} model included here removes these limitations.

In year 1987, Nishida and Sah [10], carrier mobility for MOSFET has been modeled by including surface and bulk acoustic phonon-scattering, intervalley-phonon-scattering, bulk ionized-impurity scattering, surface oxide-charge-scattering and the surface roughness scattering using the theoretical and experimental results. Both electrons and holes mobility has been taken in [10]. The velocity saturation effect is also modeled. The comparison of this model with the Selberherr model gives excellent agreement in subthreshold region and a less than about 20 percent difference in the strong inversion range. This model is used for micrometer and sub-micrometer size silicon MOSFETs. Variation of electron mobility with effective vertical electric field is shown in figure 1.

Lastly, in 2009 Luca Donetti et al. [13], the effective mobility for holes in inversion layers is computed using a one-particle Monte Carlo simulator and the Poisson solver. The optical and acoustic phonon scattering, surface roughness and the coulomb interaction due to impurities and trapped charges have been included in the model. The hole mobility versus effective electric field is shown in figure 2. Moreover, effect of uniaxial/biaxial stress on the hole mobility are also described in this model as shown in figure 3.

Effective mobility of these models are compared with the experimental results of models [5,6] in the inversion layer of MOSFETs. For micrometer size devices Ken Yamaguchi [9], gives the excellent agreement with experimental results for both electron and hole mobility.

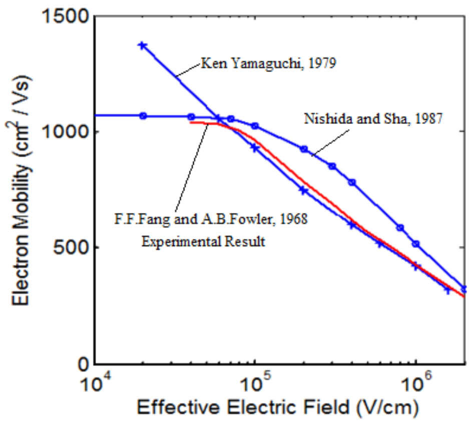

Figure 1: Variation of electron mobility with effective electric field for numerical models including experimental results of [5] is shown.

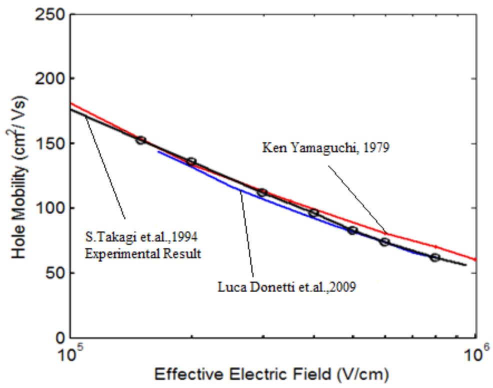

Figure 2: Variation of hole mobility with effective electric field for numerical models including experimental results of [6] is shown.

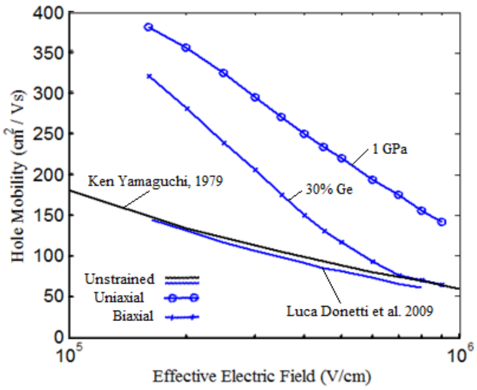

Figure 3: Variation of hole mobility of strained (biaxial for 30% Ge fraction and uniaxial for 1GPa compressive stress) and unstrained MOSFETs with effective electric field is shown.

3 Empirical Mobility Models

Several empirical models for the carrier mobility in the inversion layers of MOSFET, as a function of electric field have been reported. In 1972, Mansour et al. [3, 4], and in 1967, Caughey and Thomas [14], the effective inversion layer mobility was modeled by equation (1).

$$\mu_{eff} = \mu_0/[1 + (E_{eff}/E_{crit})^{\alpha}]^{1/\alpha} \quad (1)$$

E_{crit}, is the critical transverse electric field, $E_{crit} = 6.98 \times 10^3\ (T(K)/300)^{1.55}$ V/cm. α =1, for holes and α = 2 for electrons. In 1979, Sabins and Clemens [7] measured the effective mobility of electrons in the inverted (100) Si surface over a wide range of temperatures, gate voltages, and back-bias voltages. The measured effective mobility is calculated experimentally as a function of effective electric field at the doping concentration 2.31×10^{15} (cm^{-3}).

In 1980, Sun and Plummer [15] modeled the measured effective inversion layer electron mobility by an empirical model, described by equation (2).

$$\mu_{eff} = \mu_{max}(E_c/E_{eff})^{c_1} \quad (2)$$

Where $\mu_{max} = \mu_0 N_A/(1 + \alpha N_A Q_f)$, N_A is the doping concentration , Q_f is the oxide charge density in unit of 10^{11} cm^{-2}, the constant E_c= A e^{BQ_f} , A=2.79 $\times10^4$ V/cm , B=8.96×10^{-2} for dry oxidation, $c_1=0.313-6.05\times10^{-3}\log N_A$, μ_0 =

3490-164logN_A, and α = -1.04×10^{-1}+1.39×10^{-2} logN_A. Variation of effective mobility with effective electric field is shown in figure 5, for N_A = 1.22×10^{15}cm^{-3}.

In 1983, Schwarz and Russek [16, 17] the inversion layer electron mobility at room temperature is modeled by semi-empirical relations given in equation (3).

$$\frac{1}{\mu_{eff}} = \frac{1}{1150T^{-3/2}} + \frac{3.2\times10^{-21/2}}{z} \qquad (3)$$

Where

□=0.09$^{3/2}$+1.5×10^{-8} $(N_I/z)^{-1/4}$□$^{-1}N_f$

z = $0.039/E_{eff} + 1.24\times10^{-5}/E_{eff}^{1/3}$

□=T/300 K, N_f is the interface fixed charge density.

Variation of effective electron mobility with normal electric field is shown in figure 5, for N_A = 1.22×10^{15}cm^{-3}.

In 1988, Walker and Woerlee [19] modeled the effective mobility of carriers by semi-empirical relations using Matthiessen's rule. This model is described by a set of equations (4-7).

$$\mu_{eff}^{-1} = \mu_{ph}^{-1} + \mu_{sr}^{-1} + \mu_c^{-1} \qquad (4)$$

Where $\mu_c = \left(\frac{CT^{1.5}}{\ln(1+b)-b/(1+b)}\right)\frac{1}{N_I}$ (5)

b = $(24m^*{}_{si}k^2T^2)/(\hbar^2q^2N_A)$, N_I is charged impurity density, N_A is the mobile carrier density, C is constant, $_{si}$ is the dielectric constant of silicon and other symbols have their usual meanings.

$$\mu_{ph} = k_{ph}T^{-1}E_{eff}^{-1/3}, \qquad (6)$$

$$\mu_{sr} = k_{sr}E_{eff}^{-2} \qquad (7)$$

Constants C, k_{ph} , k_{sr} are the fitting parameters. The value of these parameters for electrons and holes is given in the model [20]. Variation of effective electron mobility with effective electric field for N_A = 2.1×10^{16}cm^{-3} is shown in figure 5. Variation of effective hole mobility with effective electric field is shown in figure 6.

In 1989, Jeon and Burk [21] the effective inversion layer mobility at room temperature is modeled by a set of equations (8-11).

$$\mu_{eff}^{-1} = \mu_{ph}^{-1} + \mu_{sr}^{-1} + \mu_c^{-1} \tag{8}$$

Where $\mu_c = a_1^{-1} T^{-1} E_{eff}^{\alpha}$, (9)

$$\mu_{ph} = a_2^{-1} T^{-n} E_{eff}^{-1/\gamma} , \tag{10}$$

$$\mu_{sr} = a_3^{-1} E_{eff}^{-2}, \tag{11}$$

and a_1, a_2, a_3 , n and are the fitting parameters are extracted at room temperature. Variation of effective mobility with effective electric field is shown in figure-5.

In 1991, Shin et. al. [22] the electron inversion layer mobility is modeled by physically-based semi-empirical relations using Matthiessen's rule described by set of equations (12-15).

$$\mu_{eff}^{-1} = \mu_{ph}^{-1} + \mu_{sr}^{-1} + \mu_c^{-1} \tag{12}$$

Where $\mu_{ph} = \left[\left(1150 T_n^{-2.5}\right)^{-1} + \left(\frac{0.0388 T_n E_{eff}^{-1} + 1.73\times10^{-5} E_{eff}^{-1/3}}{3.2\times10^{-9} p T_n^{-0.5}} \right)^{-1} \right]^{-1}$, (13)

Where $p = 0.09 T_n^{1.75} + 4.53\times10^{-8} \left(\frac{N_I}{z}\right)^{-0.25} T_n^{-1} N_f$,

$N_f = 3\times 10^{10}$ cm^{-2}, $N_I = (\varepsilon_{si}/q)(E_{eff} + E_0)$, $T_n = T/300$, E_0 is the transverse electric field at the inversion layer edge.

$$\mu_{sr} = 6 \times 10^{14} E_{eff}^{-2} \tag{14}$$

$$\mu_c = \left(\frac{K_c T_n^{1.5}}{\ln(1+\gamma_{BH}^2) - \left(\gamma_{BH}^2/(1+\gamma_{BH}^2)\right)} \right) \frac{1}{N_A} \tag{15}$$

Where $\gamma_{BH}^2 = \frac{2\times10^{[illegible]}}{N_I/Z} T_n^2$, Z is the average inversion layer width. Variation of effective electron mobility with electric field is shown in figure 5.

In 1993, Yue et al. [25] developed an improved comprehensive universal model for effective electron mobility in inversion layers of n-channel MOSFETs for circuit simulation. This model expresses the effective electron mobility at room temperature as a function of effective vertical field. The effective mobility after fitting experimental data taken at room temperature [7, 15, 23, 24] is given by equation (16).

$$\mu_{eff} = \frac{1481}{1+0.0788E_{eff}^{0.88}+2.68\times10^{-13}E_{eff}^{2}} \quad (16)$$

Variation of effective electron mobility with effective electric field is shown in figure 5.

In 1994, Huang and Arora [26] the effective inversion layer mobility at room temperature is modeled by equation (17)

$$\mu_{eff} = \mu_0/\left[1 + aE_{eff}^{1/3} + bE_{eff}^{2} + c(1 + Q_i/Q_b)^2\right] \quad (17)$$

Where the 1/3 power dependence models the acoustic phonon scattering and 2 power dependence is the surface roughness scattering, where μ_0, a, b and c are the fitting parameters. Variation of effective electron mobility with electric field is shown in figure 5.

In 1996, Cheng and Woo [27] developed a semi empirical model for electron and hole mobilities of MOSFET inversion layer. This model takes in to account the dependence of different scattering mechanism on temperature and transverse electric field over a wide range. The effective mobility is modeled by equation (18) by the same formula as proposed by Watt, et al. [28].

$$\mu_{eff}^{-1} = \mu_{ph}^{-1} + \mu_{sr}^{-1} + \mu_c^{-1}$$

$$\frac{1}{\mu_{eff}} = \frac{1}{\mu_1}\left(\frac{10^6}{E_{eff}}\right)^{\alpha_1} + \frac{1}{\mu_2}\left(\frac{10^6}{E_{eff}}\right)^{\alpha_2} + \frac{1}{\mu_3}\left(\frac{10^{18}}{N_b+Q_f/z}\right)^{-1}\left(\frac{10^{12}}{Q_{inv}}\right)^{\alpha_3} \quad (18)$$

Where N_b is substrate doping concentration, Q_f is the interface state density, and z is the width of inversion layer given by [17]. Variation of hole mobility with effective electric field is shown in figure 6.

In 1996, Chen, et al. [29] modeled the measured effective inversion layer electron mobility at room temperature by an empirical model as given in equation (19).

$$\mu_{eff} = 540/\left[1 + (E_{eff}/0.9)^{1.85}\right] \quad (19)$$

In 1997 Chain, et al. [30] modeled the effective inversion layer mobility of MOSFET based on physics of scattering mechanism. In this model the four major scattering are: 1. phonon scattering due to lattice vibration. 2. surface roughness scattering due to the microscopic roughness of the Si-Sio_2 interface; 3. coulomb scattering from ionized bulk impurities; and 4. coulomb scattering from the Si-Sio_2 interface charges. The effective mobility is given by equation (20).

$$\mu_{eff} = \mu_0 \left\{ \left(1 + U_a E_{eff}^{1/3}\right)\left(\frac{T}{300}\right)^{3/2} + U_b \left(\frac{T}{300}\right)^{-1/2} \times E_{eff}^2 (1 + U_{k1} V_{bs}) + \left(U_{c0} T E_{eff}^{-2} + U_{c1}\left(\frac{300}{T}\right) E_{eff}^{-1}\right)(1 + U_{k2} V_{bs}) \right\}^{-1} \quad (20)$$

Where U_a, U_b, U_{c0}, U_{c1}, U_{k1} and U_{k2}, are the parameters given in [30].

In 2001, Lim and Zhou [34] modeled the measured effective inversion layer mobility at room temperature by a physically based semi-empirical model given by equation (21).

$$\mu_{eff}^{-1} = \mu_{ph}^{-1} + \mu_{sr}^{-1} + \mu_c^{-1}$$

$$\mu_{eff} = \frac{\mu_1}{1 + (\mu_1/\mu_2) E_{eff}^{1/3} + (\mu_1/\mu_3) E_{eff}^{2}} \quad (21)$$

Where $\mu_1 = \mu_c$, coulombic mobility can be assumed as a constant, $\mu_2 = BN^{Ym}/T$ and $\mu_3 = CN^{Ym}$.

In 2002, Remashan, et al. [35] modeled the inversion layer carrier mobility in all regions of MOSFET operation with the help of a 2-D drift and diffusion device simulator. In this empirical model two expressions are employed for mobility, one for the universal part, [36] and other for the non universal part [37]. Using the Matthiessen-rule, the resulting mobility is given by equation (22)

$$\mu_{eff}^{-1} = \mu_{uni}^{-1} + \mu_{non-uni}^{-1} \quad (22)$$

Where, for electron

$$\mu_{uni} = \frac{600\left(1 - \frac{V_{bs}}{35.5}\right)}{1 + \left(\frac{E_{eff}}{0.7}\right)^{1.6}} \; cm^2/Vs$$, and

$$\mu_{non-uni} = [250 - (100 V_{bs})] + 300\left(\frac{N_i}{10^{11}}\right) \; cm^2/Vs$$

For holes

$$\mu_{uni} = \frac{192\left(1 + \frac{V_{bs}}{55}\right)}{1 + \left(\frac{E_{eff}}{0.45}\right)^{1.15}} \; cm^2/Vs$$, and

$$\mu_{non-uni} = [100 + (40 V_{bs})] + 70\left(\frac{N_i}{10^{11}}\right) \; cm^2/Vs$$,

N_i is the electron/hole concentration per unit area in the inversion layer. Variation of hole mobility with effective electric is shown in figure 6.

In nano scale devices the mobility of carriers can be increased by using the strained silicon technology. When oxide thickness is below approximately 10nm, carrier mobility is degraded [38]. In 2005, Lauer and Antoniadis [39] the effective mobility was extracted using equation (23).

$$\mu_{eff} = LI_D / WQ_iV_{DS} \tag{23}$$

Where Q_i is determined by integration of high frequency C-V characteristic and V_{DS} is the effective source/drain voltage. Mobility enhancement with applied strain for different inversion layer densities is given in the model [39]. All devices show a linear mobility enhancement with strain. The thick devices shows similar enhancement at low and high fields. The thin device shows more enhancement than the thick device dose, especially at low field.

In 2004, Wei Zhao, et al. [40] the effect of tensile uniaxial strain on the DC performance of partially-depleted silicon on insulator n and p-channel MOSFETs are reported. The drain current of the n-MOSFETs increases for both longitudinal and transverse strain orientations with respect to the current flow direction. In n-MOSFET, longitudinal strain provides greater enhancement than transverse strain. For p-MOSFETs, longitudinal strain decreases the current while transverse strain increases the drain current. A change in drain current with strain can result from changes in the effective mobility. The effective mobility is given by the equation (24)

$$\mu_{eff} = LI_D / [WC_{ox}V_{DS}(V_{GS} - V_T)] \tag{24}$$

The threshold voltage V_T, is linearly extrapolated from the point of maximum transconductance [41]. The effective vertical field is calculated from using $E_{eff} = (V_{GS} + V_T)/6T_{ox}$ for n-channel, and $E_{eff} = (V_{GS} + 1.5V_T)/7.5T_{ox}$ for

p-channel devices [42]. The extracted electron and hole effective mobility versus effective vertical effective electric field is shown in figure 4.

Several empirical and semi-empirical mobility models are compared with the experimental results of model [6]. Sun and Plummer [15], Schwarz and Russek [16, 17] and Shin et. al. [22] models give the excellent match with experimental results for electron mobility. All other models are also gives good match with experimental results. For hole mobility Chen, et al. [29] model gives the excellent match with the experimental results.

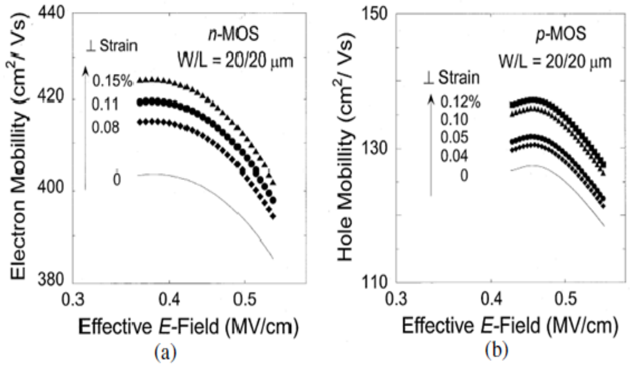

Figure 4: (a) Extracted electron and (b) hole effective mobility versus effective vertical field for n-MOSFET under transverse strain [40].

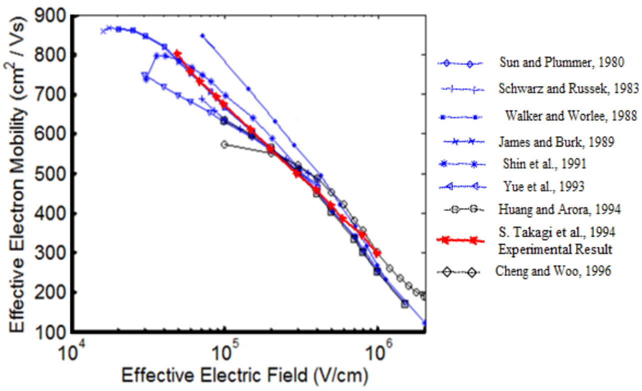

Figure 5: Variation of effective electron mobility in the inversion layer of MOSFET with effective electric field including experimental results of [6] for empirical and semi-empirical models is shown.

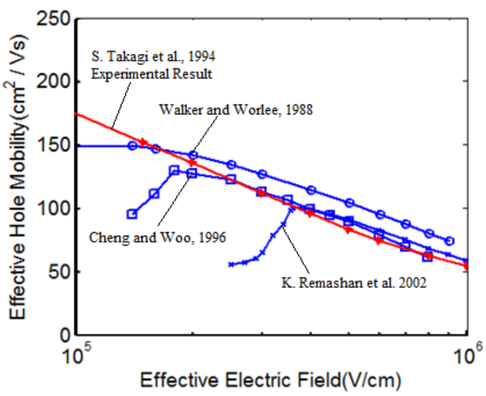

Figure 6: Variation of effective hole mobility in the inversion layer of MOSFET with effective electric field including experimental results of [6], for various empirical and semi-empirical models is shown.

4 Analytical Mobility Models

Carrier mobility in the inversion layers of MOSFET have been described analytically. Several analytical models for the mobility of carriers in the inversion layers of MOSFET have been reported.

In 1992, D.B.M. Klaassen [43], represented the first physics-based analytical model that unifies the description of majority and minority carrier mobility and that includes screening of impurities by charge carriers, electron-hole scattering and clustering of impurities. In this model the electron and hole mobility are given as analytical functions of local variables: ionized donor, ionized acceptor, electron and hole concentrations.

In 1998, S. Villa, et al. [44] the effective inversion layer mobility is modeled by analytical relations for heavily-doped ULSI MOSFETs using Matthiessen's rule as described by equations (25-28).

$$\mu_{eff}^{-1} = \mu_{ph}^{-1} + \mu_{sr}^{-1} + \mu_{c}^{-1} \quad (25)$$

$$\mu_{ph} = \mu_{phb}\left[\left(\frac{T}{300K}\right)^{n} + \left(\frac{T}{300K}\right)^{r}\left(\frac{E_{eff}}{E_0}\right)^{\alpha(T)}\right]^{-1} \quad (26)$$

Where $\mu_{phb}(300K) = 1470cm^2V^{-1}s^{-1}$ is the phonon limited bulk mobility,

n=2.109, r=1.7, $E_0 = 7\times 10^4$ V/cm and $\alpha(T) = 0.2(T/300)^{-0.1}$

$$\mu_c = F^2\mu_0\frac{F}{N_A L_{th}}\left(1 + \frac{L_{th}}{F.L_s}\right)^2 \quad (27)$$

Where L_{th} is called the thermal length, L_s is called the screening length and F is the ratio between Debye-Huckel and effective screening length.

$$\mu_{sr} = \frac{\delta \exp\left(-(T/T_0)^2\right)}{E_{eff}^{2}} \quad (28)$$

Where δ and T_0 are the fitting parameters. The effective mobility as a function of effective electric field is shown in figure 7.

In 2007, N.Rodriguez, et al. [45] the analytical expression for the mobility carried out by using the Matthiessen's rule:

$$\mu_{eff}^{-1} = \mu_{ph}^{-1} + \mu_{sr}^{-1} + \mu_{\pi}^{-1} \quad (29)$$

The remote scattering mobility component (μ_{π}) given in equation (2) in the model, the Si-Sio$_2$ surface roughness mobility component (μ_{sr}) given in equation (5) by an analytical expression in the model and the phonon scattering mobility component given in equation (6) in the model. Variation of electron mobility including phonon, interface roughness, coulomb scattering, remote roughness and coulomb scattering due to polysilicon depletion charge with electric field at room temperature for doping concentration=3x10^{16} cm^{-3} is shown in figure 7.

In 2011, M.H.Bhuyan and Q.D.M. Khorsu [46] modeled the inversion layer mobility for pocket implanted nano scale n-MOSFETs. The effective mobility for nano MOSFET is given by equation (30) using the Matthiessen's rule:

$$\mu_{eff}^{-1} = \mu_{equ}^{-1} + \mu_{bal}^{-1} \quad (30)$$

Where, $\mu_{bal} = 2qL/\pi m_{n,eff} v_{th}$, is the ballistic mobility, and

$\mu_{equ}^{-1} = \mu_{ph}^{-1} + \mu_{sr}^{-1} + \mu_{c}^{-1}$ is the total mobility that consider the effect of

all scattering mechanisms. The effective mobility in (nano scaled) MOSFETs must be much smaller than the electron mobility in long channel devices. This reduction was predicted for ballistic devices in [47-49]. Variation of effective electron mobility with the effective electric field is shown in figure 7.

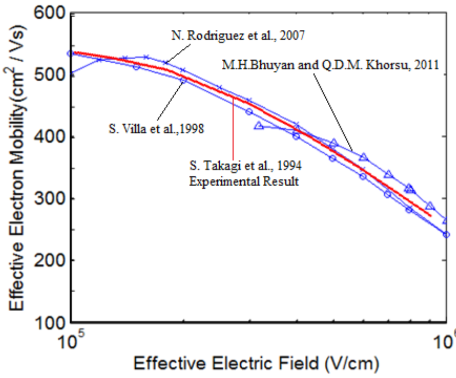

Figure 7: Variation of effective electron mobility with effective electric field for various analytical models including experimental results of [6] for analytical models is shown.

To enhance the mobility in the inversion layer of MOSFETs, strained-Si is regarded as possible alternatives to conventional Si devices mostly for deep submicron devices. In 2003, J.B.Roldan, et al. [50] mobility is modeled for strained-Si MOSFETs accounting for various scattering mechanisms such as surface roughness scattering, phonon scattering and coulomb scattering.

Phonon scattering due to the lattice vibrations is given by equation (31).

$$\frac{1}{\mu_{ph}} = \frac{1}{\mu_{phB}\beta(x)}\left[1 + \left(\frac{E_{EFF}}{E_0}\right)^{0.2\alpha(x)}\right] \quad (31)$$

$$\mu_{phB} = 1470\, cm^2/Vs$$

$$E_0 = 2 \cdot 10^4\, V/cm$$

$$\alpha(x) = \frac{a_\beta x}{\left(1+\left(\frac{a_\beta x}{4.7}\right)^{b_\alpha}\right)^{1/b_\alpha}} + 1$$

$$\beta(x) = \frac{a_\beta x}{\left(1+\left(\frac{a_\beta x}{2.7}\right)^{b_\beta}\right)^{1/b_\beta}} + 1$$

$$a_\alpha = 3\ , b_\alpha = 25\ , a_\beta = 11\ , \ b_\beta = 15$$

Surface roughness scattering due to the microscopic roughness of the Si–SiO_2 interface is given by equation (32).

$$\mu_{sr} = \frac{\delta(x)10^{14}}{E_{EFF}^{2}} \qquad (32)$$

$$\delta(x) = \frac{a_\delta x}{\left(1+\left(\frac{a_\delta x}{\Delta_\delta}\right)^{b_\delta}\right)^{1/b_\delta}} + \delta_0$$

$a_\delta = 7\ , \ b_\delta = 15\ , \ \Delta_\delta = 2.1\ , \delta_0 = 3.8$ Coulomb scattering due to impurity

scattering is given by equation (33).

$$\frac{1}{\mu_c} = C\frac{N_A}{N_s} \qquad (33)$$

$C = 45.45 \cdot 10^{-9}$ Vcm^{-1}

$N_A = 5 \cdot 10^{23}\ , \ N_s = \frac{Q_{inv}}{q}$

Q_{inv} is the inversion charge density
N_A = Doping concentration (cm^{-3}).
The total mobility of the electrons is calculated as follows from the mathiessen's rule:

$$\mu_{eff}^{-1} = \mu_{ph}^{-1} + \mu_{sr}^{-1} + \mu_c^{-1} \qquad (34)$$

The electron mobility versus effective field for strained-Si on $Si_{1-x}Ge_x$ MOSFETs at room temperature for x=0 and x=0.2 is shown in figure 8.

In 2004, Z.Yang, et al. [51] developed an electron and hole mobility analytical model for strained silicon MOSFETs. The mobility enhancement for both electrons and holes in strained silicon layers is studies by analytical expressions. It can be used in simulations to study the ultra-small strained silicon devices.

Several analytical models are compared with the experimental results of model [6] in figure 7. S. Villa, et al. [44], model gives the excellent match with the experimental results.

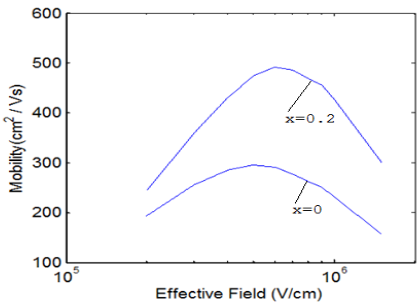

Figure 8: variation of electron mobility with effective field for strained-Si on $Si_{1-x}Ge_x$ MOSFETs at room temperature.

5 Summary of Models

The below given table 1 summarizes all the mobility models described in earlier sections of the paper.

Table:1

Year	Model given by	Type of Model	Mobility for Electron/Hole (cm^2 / Vs)	Effective Electric Field (V/cm)
1968	Fang and Fowler	Experimental (unstrained)	955 (electrons)	10^5
1979	Ken Yamaguchi	Numerical (unstrained)	930 (electrons)	10^5
1987	Nishida and Sha	Numerical (unstrained)	1035 (electrons)	10^5
1979	Sabins and Clemens	Experimental (unstrained)	800(electrons)	10^5
1980	Sun and Plummer	Empirical (unstrained)	665 (electrons)	10^5
1983	Schwarz and russek	Semi-empirical (unstrained)	666 (electrons)	10^5
1988	Walker and Woerlee	Semi-empirical (unstrained)	730 (electrons)	10^5
1989	Jeon and Burk	Semi-empirical (unstrained)	642 (electrons)	10^5
1991	H.Shin et al.	Semi-empirical (unstrained)	700 (electrons)	10^5
1993	C.Yue et al.	Empirical (unstrained)	630 (electrons)	10^5
1994	Huang and Arora	Empirical (unstrained)	570 (electrons)	10^5
1994	S. Takagi et al.	Experimental (unstrained)	776 (electrons)	10^5
1996	B.Cheng and J.Woo	Semi-emperical (unstrained)	635 (electrons)	10^5
2001	Lim and Zhou	Semi-empirical (unstrained)	340 (electron)	10^5
2002	K.Remashan et al.	Empirical (unstrained)	170 (electron)	10^5
1998	S.Villa et al.	Analytical (unstrained)	534 (electron)	10^5
2007	N.Rodriguez et al.	Analytical (unstrained)	502 (electron)	10^5
2011	Bhuyan and Khorsu	Analytical (unstrained)	345 (electron)	10^5
2003	J.B.Roldan et al.	Analytical (biaxial for x=0.2)	430 (electron)	4×10^5
2003	J.B.Roldan et al.	Analytical (biaxial for x=0)	285 (electron)	4×10^5
2004	Z.Yang, et al.	Analytical (biaxial for x=0.3)	720 (electrons)	4×10^5
2004	Z.Yang, et al.	Analytical (biaxial for x=0.2)	120 (holes)	4×10^5
1979	Ken Yamaguchi	Numerical (unstrained)	180 (holes)	10^5
2009	Luca Donetti et al.	Numerical (unstrained)	160 (holes)	10^5

2009	Luca Donetti et al.	Numerical (uniaxial for 1GPa)	390 (holes)	10^5
2009	Luca Donetti et al.	Numerical (biaxial for 30% Ge)	328 (holes)	10^5
1988	Walker and Woerlee	Semi-empirical (unstrained)	127 (holes)	4×10^5
1994	S. Takagi et al.	Experimental (unstrained)	97 (holes)	4×10^5
1996	B.Cheng and J.Woo	Semi-empirical (unstrained)	100 (holes)	4×10^5
2002	K.Remashan et al.	Empirical (unstrained)	98.5 (holes)	4×10^5

Discussion:

From this summery of models we can select an accurate model for device simulation and analysis for various technology modes. Out of numerical models, Ken Yamaguchi [9], model gives the excellent match with the experimental model. Luca Donetti et al. [13] shows the enhancement of hole mobility due to uniaxial and biaxial strain. In empirical models, Sun and Plummer [15], Schwarz and Russek [16, 17] and Shin et. al. [22] models give the excellent match with experimental results for electron mobility. For hole mobility Chen, et al. [29] model gives the excellent match with the experimental results. Wei Zhao, et al. [40] model shows the enhancement in mobility due to strain. Out of analytical models, S. Villa, et al. [44] model, gives the excellent match with experimental model. J.B.Roldan, et al. [50] shows the enhancement of mobility due to biaxial stain silicon.

6 Conclusion

A critical review of analytical, empirical and numerical models for the effective mobility of charge carriers in MOSFET inversion layer (p and n type) has been done. It has been found that the carrier mobility in strained silicon MOSFETs is higher than the unstrained silicon MOSFET. Certain models have been identified to be applicable for mobility determination in strained and unstrained MOSFETs.

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