Quantum Effects Investigation in 20 nm Gate Underlap SOI MOSFET for Millimeter Wave Applications

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Abstract This paper presents the investigation of quantum effects of gate underlap 20nm Silicon-On-Insulator (SOI) MOSFETs at 60 GHz. At optimized spacer $s = 0.8L_G$ with doping gradient $d = 5\text{nm/decade}$ the device DC and AC performances have been investigated with and without quantum effects. After incorporation of quantum effects, at 60 GHz the device current gain, unilateral gain (ULG) and device intrinsic gain are found 50 dB, 70 dB and 36dB respectively at power consumption 0.6 mW. All these parameters have been extracted using 2D ATLAS device simulator. The average 50% performance of device has been increased after incorporating quantum effects model. Although simulated result for current gain nearly 25% higher than measured data (gate length $L_G = 20\text{nm}$) whereas for transit frequency f_T is differ (>13%). However, these comparisons with limited measured data suggest the possibility of use of this device technology in the design of key blocks like low noise amplifier (LNA) and Mixer for mm-w applications.

Keywords Quantum Effects, Underlap, Silicon-On-Insulator, Millimeter Wave

1. Introduction

In the past few years, low-power low-voltage silicon-on-insulator (SOI) MOSFET technology has emerged as a leading candidate for highly integrated circuits for wireless applications [1]. However, below the 20 nm technology node, upcoming CMOS technologies face many technological challenges, the most crucial being the short channel effects (SCEs) that tend to degrade sub threshold characteristics and increase leakage current because of quantum effects [2]. The influence of film-thickness reduction on the threshold voltage of single and double-gate SOI MOSFETs has been reported in the literature [3]. It is found that, due to quantum confinement of carriers in a thin silicon layer, the minimum energy for electrons in the conduction band increases when

the thickness of the silicon film is reduced [4]. As a result, the threshold voltage increases as the film thickness is reduced. This effect was first predicted by Omura *et al.* in 1993, and has been simulated and observed experimentally by several groups since [5]. It is included in modern thin-film SOI and double-gate MOSFET simulators [6].

In this paper, we report a similar effect in n-channel single gate underlap fully depleted SOI MOSFETs. The threshold voltage increases when the cross section of the device is decreased—due to quantum-confinement effects. Furthermore, the minimum energy for the electrons in the conduction energy sub-bands increases with the electron concentration, which dynamically increases the threshold voltage as the inversion charge builds up [7-8]. This effect reduces the current drive of the device and is not predicted by classical simulators. That's for solving such a problem we need to add a self-consistent Poisson-Schrödinger solver for more explanation about that has been given in section-2. The effects of quantum at high frequency (> 60 GHz) has been observed and discussed in section-4.

2. What is Quantum Effects?

To adequately predict quantum effects due to the formation of energy sub bands, it is necessary to solve the Poisson equation and the Schrödinger equation self-consistently [9]. The Poisson equation is given by.

$$\nabla^2 \Phi(x, y) = -\frac{q}{\epsilon_{si}} [p(x, y) - n(x, y) + N_D - N_A] \quad (1)$$

in the silicon and the silicon dioxide

$$\nabla^2 \Phi(x, y) = 0 \quad (2)$$

In these equations, Φ , p , n , N_D , and N_A are the potential (V), hole concentration (m^{-3}), electron concentration (m^{-3}), donor atom concentration (m^{-3}), and acceptor atom concentration (m^{-3}), respectively. The doping impurity concentrations, N_A and N_D , are considered to be constant. The Schrödinger equation is written.

$$\left(\frac{\hbar^2}{2m_{ds}^*}\nabla^2 - q\Phi(x,y)\right)\Psi_j(x,y) = E_j\Psi_j(x,y) \quad (3)$$

Where m_{ds}^* is the density-of-states electron mass, and E_j and Ψ_j are the minimum energy and the wave function of the j_{th} sub band, respectively. The density-of-states electron mass is defined by $m_{ds}^* = 6^{\frac{2}{3}} (m_t^* m_l^*)^{1/3} = 1.08 m_0$ where m_t^* and m_l^* are the transverse and longitudinal electron masses in a three-dimensional (3-D) silicon crystal [10-11]. Different mass values can be used to describe more accurately devices made along particular crystal orientations [12], but the general results and conclusions presented here are qualitatively applicable to any orientation. The Schrödinger equation is solved both in the silicon and the silicon dioxide, with boundary conditions insuring the continuity of the wave functions at the Si/SiO₂ interfaces. The electron concentration is obtained by adding the electron concentrations of all sub bands. Since sub bands located at an energy more than 10 kT above the minimum of the conduction band have a negligible electron population, we confine the calculation of the electron density to energies ranging from EC to $EC + 10$ kT. The electron concentration is thus given by [12]

$$n(x,y) = \sum_j |\Psi_j(x,y)|^2 \Psi_j^*(x,y) \int_{EC}^{EC+10KT} \rho_j(E) f_{FD}(E) dE \quad (cm^{-3}) \quad (4)$$

where $\rho_j(E)$ is the density of states in the j_{th} sub band $f_{FD}(E)$ is the Fermi–Dirac distribution function. The density of states used in the simulations corresponds to that of a one dimensional structure [13].

$$\rho_j(E) = \frac{1}{\pi A_{Si}} \sqrt{\frac{2m_{ds}^*}{\hbar^2}} \frac{1}{\sqrt{E-E_j}} \quad (cm^{-3}J^{-1}) \quad (5)$$

Where A_{Si} is the cross-sectional area of the silicon film. The Fermi–Dirac distribution is given by the familiar expression.

$$f_{FD}(E) = \frac{1}{1 + e^{\frac{E-E_F}{kT}}} \quad (6)$$

Since only sub-bands with energy less than 10 kT above the minimum of the conduction band are populated with a significant number of electrons, the number of sub bands N used in each calculation is limited and can be calculated from the silicon cross-sectional area and the temperature. The following expression is used to calculate the discrete integer of bands [13].

$$N = \frac{10 kT m_{ds}^* A_{Si}}{\pi^2 \hbar^2} \quad (7)$$

A cross section of the simulated device and the number of sub-bands corresponding to a MOSFET with square cross section (i.e., the silicon width W is equal to the silicon

thickness T_{si}). The Poisson equation is first solved with $n(x,y) = 0$ as initial condition. The resulting potential distribution is fed into the Schrödinger equation to calculate the two-dimensional (2-D) wave functions and their energy levels. Using this information, the electron concentration $n(x,y)$ is calculated using (4). The electron concentration is then introduced in the Poisson equation and a Newton–Raphson iteration process is used until convergence of the electron concentration is obtained. The criterion for convergence is a variation of electron concentration less than 0.1% between two iterations.

3. Device under Study

At mm-w frequencies, the device optimization has a significant impact on importance of the overall performance. As a result, careful device design becomes quite important in pushing the capability of nano-scale SOI to higher GHz range (>10GHz). This section describes the device design intended to optimize the device physical structure in terms of spacer width s and doping gradient d as shown in Fig. 1a. Device structure comprises of a gate length $L_G = 20$ nm, gate oxide thickness $t_{ox} = 1.5$ nm and buried oxide thickness $t_{box} = 106.5$ nm. The p-type doping used on SOI layer has doping equal to 10^{16} cm⁻³ for adjusting a low value of threshold voltage $V_{TH} = 0.26$ V, which is required for low power applications. The undoped device (Fig. 1a) with mid band metal gate work function equal to 4.72 eV has been simulated using 2D ATLAS simulator [14]. This device has been optimized to simultaneously maximize the transit frequency f_T and voltage gain A_v and corresponding values for s and d , which has been found equal to $0.8 \times L_G$ and 5 nm/decade, respectively [6]. In order to keep the device almost free from short channel effect, the natural length

$\gamma = \sqrt{\frac{\epsilon_{si}}{\epsilon_{ox}}} t_{ox} t_{si}$, where ϵ_{si} and ϵ_{ox} are permittivity of silicon and oxide [15], was chosen equal to one seventh of L_G . Source/drain profile used in the device was modeled using a

lateral Gaussian Profile $N_{SD}(x) = (N_{SD})_{peak} \exp\left(-\frac{x^2}{\sigma^2}\right)$ where $(N_{SD})_{peak}$ is the peak source/drain doping; lateral straggle σ

defines the roll-off of source/drain profile as $\sigma = \sqrt{\frac{2sd}{\ln(10)}}$,

where d is evaluated at the gate edge $d = 1/|dN_{SD}(x)/dx|$ [16]. The doping gradient of the designed device along cut line in the channel region is shown in Fig. 1b. The optimal underlap profile for better analog/RF performance is obtained with spacer to straggle ratio $s/\sigma = 4$ is used.

Figure 1a. Structure of optimized device simulated in ATLAS

Figure 1b. Illustration of an under lap S/D profile (x - x) of optimized device with $d = 5 \text{ nm/dec}$, $s = 0.8 \times L_G$, $V_{GS} = 0.4$, $V_{DD} = 1 \text{ V}$.

4. Results Analysis

Quantum effects in underlap SOI MOSFET has been observed for millimeter wave applications. A self-consistent Poisson–Schrödinger solver is used to solve the quantum effects. In Table-1 the data are tabulated the performance of device before and after adding quantum effects model. Fig-2a shows that drain current has been increased after adding the quantum model and has become 0.575 mA but before addition of quantum model it is a 0.05 mA this increment of current is due to use of quantification effects inside the channel and movement of electron inside the channel ballistic not drift–diffusive .

Figure2a. Plot of drain current I_{ds} (mA) vs. gate source Voltage V_{gs} (V).

Figure2b. Plot of drain current I_{ds} (mA) vs. Drain source Voltage V_{ds} (V).

From Fig-3a and 3b it can be concluded that transconductance g_m and output conductance g_{ds} of device is constant up to frequency of interest 60 GHz and also it maintains the intrinsic gain of device 36dB.

Figure3a. .Plot of transconductance g_m (mS) vs. Frequency (GHz)

Figure3b. Plot of output conductance g_{ds} (mS) vs. Frequency (GHz).

The most important figure of merit of MOSFETs at millimeter wave frequencies is the current gain ($|H_{21}|$), which is given by [17-18]

$$|H_{21}| = \left| \frac{Y_{21}}{Y_{11}} \right| \quad (8)$$

The unilateral gain (ULG) is defined as the maximal available gain of a device when the stability is ensured by using a lossless feedback network to cancel the reverse transmission of the device. From the different gain expressions defined above, it is possible to introduce two important figures-of merit: the cut-off frequency of the current gain (f_T) and the cutoff frequency of the maximum power gain also referred to as the maximum oscillation frequency (f_{MAX}). f_T is extracted as the frequency at which short-circuit current gain $|H_{21}|$ becomes equal to unity or 0 dB. Considering the simplified small signal equivalent circuit presented in Fig. 5 f_T can be approximated by the following relation.

$$f_T \cong \frac{g_m}{C_{gs} + C_{gd}} \quad (9)$$

Note that f_T is only dependent on the intrinsic parameters of the MOSFET. Then it is an important factor to compare different technologies and devices, f_T measure the intrinsic bandwidth of the device. The maximum frequency of oscillation f_{MAX} is defined as the frequency for which the unilateral gain (ULG) becomes equal to unity or 0 dB and approximated by following relation [10]:

$$f_{MAX} \cong \frac{f_T}{2\sqrt{2\pi f_T R_{ge}(C_{gd} + C_{gde}) + g_{ds}(R_{ge} + R_{se} + R_{gsi})}} \quad (10)$$

Fig. 4a and 4b shows the current gain and unilateral gain before and after adding the quantum effects and it has been found that approximately the value of current gain and unilateral gain after adding quantum effect has become just double.

Figure 4a. Plot of current gain (dB) vs. frequency (GHz) at optimized bias

Figure 4b. Plot of unilateral power gain (dB) vs. frequency (GHz) at optimized bias

Fig.4c shows the plot of f_T and f_{MAX} which is extracted by 2D ATLAS simulator [14] and for authentication of data these extracted results has been compared with measured data [6] and found nearly 13% increased.

Figure 4c. Plot of f_T , f_{MAX} (GHz) vs. frequency of interest (60 GHz)

Table 1. Device performance results at optimized bias.

Data	With quantum	Without quantum
I_{ds} (mA)	0.575	0.05
g_m (mS)	452	42
g_{ds} (mS)	0.112	6.98
Current gain (dB)	16.39	38.2
ULG (dB)	38.74	56.48
I_{on}/I_{off}	3.80	0.2

5. Conclusions

The enormous potential of source drain extension region engineering in 20 nm SOI MOSFETs for millimeter wave applications has been extensively analyzed for 20 nm gate length. A self-consistent Poisson-Schrödinger solver was used to calculate the current in n-channel SOI transistors. The minimum energy of the subbands and the threshold voltage increase as the cross-sectional area of the device was reduced and as the electron concentration in the channel was increased. As a consequence, the threshold voltage was higher than predicted by classical Poisson Solvers. It has been found that the presence of optimal spacer length $s = 0.8L_G$ does not degrade the performance of device. This optimal spacer reduces feedback capacitance sufficiently to enhance intrinsic gain of device as well as both f_T and f_{MAX} . It has been observed from results that after adding quantum effects 50% performance of device has been increased. The device is maintained the current gain and ULG 50 and 70 dB respectively with power consumption 0.6mW. So these results suggest the suitability of this technology to design of mm-w front end key blocks like low noise amplifier (LNA) and Mixer.

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