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Analytical model for subband engineering in undoped double gate MOSFETs

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1. Introduction

In conventional MOSFET bulk devices, when decreasing the channel length, the control of SCE and DIBL along the ITRS roadmap requires a constant increase of channel doping, very prejudicial for carrier mobility and on state current performances. Ultra Thin Body (UTB) devices however, and especially in multi gate structure, have the great advantage to allow a better control of short channel effects even in undoped channel, by an extreme reduction of the body thickness (t_{si} <15 nm) [1].

In such highly scaled and undoped UTB-MOSFETs quasi-ballistic transport is expected, which may improves on state performances. However, even a crude estimation of the impact of quasi ballistic transport on I_{on} current must account for the additional quantum confinement occurring in UTB devices, due to the extreme thickness of the silicon film when t_{si} < 10 nm. This effect both degrades the inversion charge and improves the injection velocity [2].

In this paper, an original model for quantization in symmetrical double gate devices is presented, allowing a complete description of the impact of subband engineering on quasi ballistic transport. This model is then applied to predict I_{on} current along the High Performance Roadmap.

2. Analytical model for quantization

The accurate modeling of available inversion charge versus applied bias including quantum effects usually requires the numerical solution of the self consistent Poisson and Schrödinger equations (P.S). However, an analytical solution of the both equations, can be achieved, noticing that : 1°/ In depletion and weak inversion regime, the solution of the Schrödinger equation are simply given by :

$$\varphi_n(x) = \sqrt{\frac{2}{t_{si}}}\sin\left(\pi\, n\frac{x}{t_{si}}\right) \quad E_n^0 = \frac{h^2\, n^2}{8\, m\, t_{si}^{\,2}} \quad n \geq 1 \qquad (1)$$

2°/ In strong inversion, for t_{si} < 7 nm, the potential energy V in the film has typically a parabolic shape in double gate devices (Fig. 1), leading to the following approximated solution of the Poisson equation :

$$V(x) = V_s + 4\frac{\Delta V}{t_{si}}x\left(1-\frac{x}{t_{si}}\right) \qquad (2)$$

where V_s and ΔV are parameters to calculate self consistently with the charge.

The Schrödinger equation with such potential term is then projected on the basis of orthogonal wave function φ_n, leading to the following set of algebraic coupled equations :

$$\left(E_k^0 - E\right)\cdot a_k + \sum_n a_n V_{nk} = 0 \qquad (3)$$

where $a_n = \langle \varphi_n | \Psi \rangle$ are the scalar product between φ_n and a possible solution Ψ of the Schrödinger equation, E the corresponding energy level, and V_{nk} the following matrix element :

$$V_{nk} = \frac{2}{t_{si}}\int_0^{t_{si}} \sin\left(\pi\, n\frac{x}{t_{si}}\right) V(x) \sin\left(\pi\, k\frac{x}{t_{si}}\right) dx \qquad (4)$$

$$V_{nk} = -\Delta V\cdot\left(16\, n\, k\cdot\frac{(-1)^{n+k}+1}{\pi^2 (n-k)^2 (n+k)^2}\right) \quad (n \neq k) \qquad (5)$$

$$V_{nn} = \Delta V\left(\frac{2}{3}+\frac{2}{n^2\pi^2}\right) \qquad (6)$$

The set of equations (3) can be reduced in only two 2 × 2 determinants, leading to analytical expressions for the first primed and unprimed energy levels, noticing that 1°/ V_{nk}=V_{kn} , 2°/ due to the symmetry of the device V_{nk}=0 for n + k =odd, 3°/ for n, k >>1, V_{nk} tends to 0. This procedure is closed to the standard quantum perturbation theory [3] (except that in this case, other approximations are used to solved Eq. (3)), but significantly more accurate, as it exploits efficiently the symmetry of the structure.

For thicker body devices (t_{si} >7 nm) however, the later approach is no longer accurate, as Eq. (2) for the potential is no longer valid (Fig.1). The former procedure can be however extended up to t_{si} = 15 nm, by improving Eq (2) with the following expression :

$$V(x) = V_s + a\, kT \ln\left(1+\frac{4\,\Delta V\cdot\left(x\cdot(1-x/t_{si})\right)}{a\, kT\, t_{si}}\right) \qquad (7)$$

where a is a fitting parameter extracted from simulations, depending on the body thickness t_{si}. Note that Eq (7) reduces to Eq (2) when t_{si} < 7 nm. Matrix elements V_{nk} are non longer analytical and have to be numerically computed. Finally, as the differences between neighbor energy levels E_n - E_k tends to decrease when incresing t_{si}, an higher number of coupled equations (3) have to be considered. Analytical expression for the first energy levels can still be obtained with an acceptable accuracy by an analytical solution of two 3 × 3 determinants.

3. Results and discussion

Comparisons between analytical and numerical energy levels are shown in Fig. 2 (for t_{si} = 5 nm), and in Fig. 3 (for t_{si} = 15 nm). A satisfactory agreement between the two results has been obtained, leading to a correct modeling of the inversion charge (Fig. 4), including both the threshold voltage shift and dark space effects due to quantization. As shown in Fig. 5 and 6, this approach also allows a correct modeling of carrier repartition on the three main subbands, which is extremely important to get a correct modeling of both electron concentration (Fig. 5 and 6) and transport properties (Fig 7).

Ballistic current has been computed following the approach proposed by Natori [4], accounting for the quantized nature of the density of states. Scattering has been included in the Lundstrom fashion, using the formula given in [5] for the back scattering coefficient r. Mobility needed to calculate r has been taken from available data on undoped UTB devices operating in the double gate mode [6], for the corresponding effective field.

The following model has been used to predict performances of the 2003 High Performance ITRS roadmap. Ballistic, quasi ballistic and quasi ballistic current accounting for series resistance have been computed (Fig. 8). Our results show a significant improvement of performance due to quasi ballistic transport (except for the final node 22 nm, where the results obtained by the present model and the ITRS are very close, because of the high value of ITRS ballistic improvement factor (1.2) on this particular node). The increasing impact of quantum confinement along the ITRS roadmap (due to the increase of effective field and the reduction of t_{si}) is highlighted on Fig. 9, showing both a degradation of the dark space, but also a more significant and benefic improvement of the injection velocity.

References

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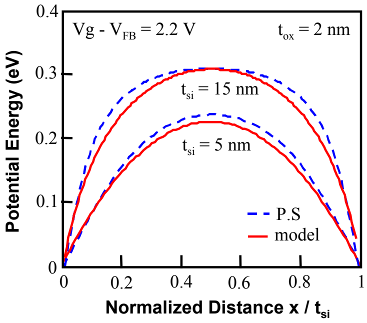

Fig1 : Potential Energy versus normalized distance for both t_{si} = 5 nm (parabolic) and t_{si} = 15 nm (highly non parabolic)

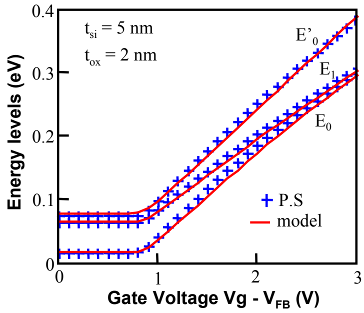

Fig 2 : Energy levels versus applied gate voltage (t_{si} = 5 nm) (cross Poisson Schrodinger simulation, line this model)

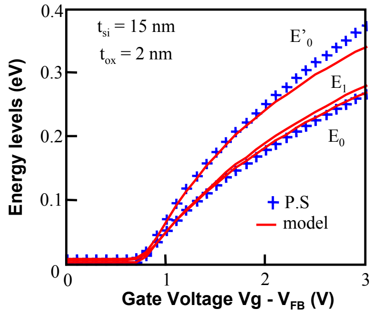

Fig 3 : Energy levels versus applied gate voltage (t_{si} = 15 nm) (cross Poisson Schrodinger simulation, line this model)

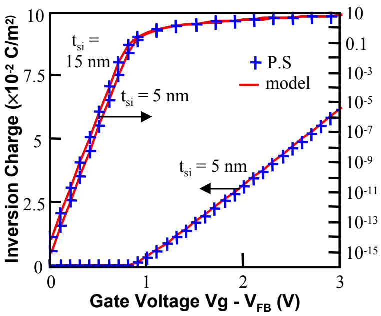

Fig. 4 : Inversion charge in linear and log scale versus gate voltage

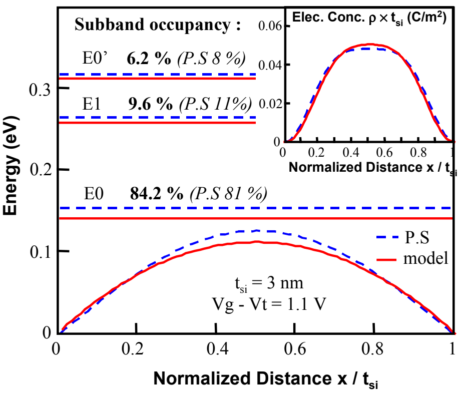

Fig. 5 : Potential energy versus distance x / t_{si} for tsi = 3 nm. The position of energy levels in the conduction band, with the corresponding occupancy are also indicated.

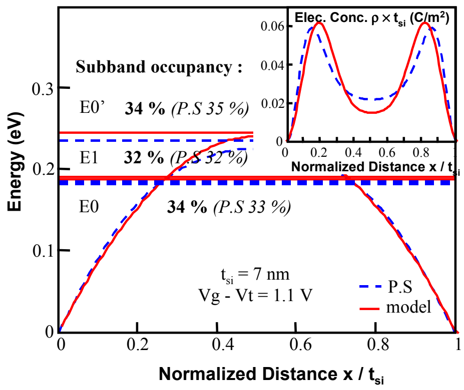

Fig. 6 : Potential energy versus distance x / t_{si} for tsi = 7 nm. The position of energy levels in the conduction band, with the corresponding subband occupancy are also indicated.

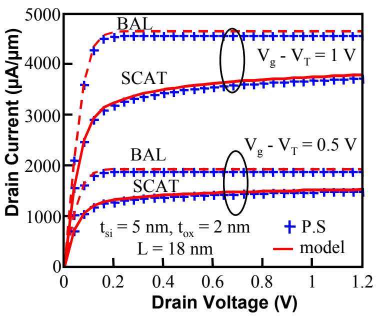

Fig 7: Drain Current versus Drain Voltage, for both ballistic simulation (BAL) and including scattering (SCAT, μ_{eff} = 290 $cm^2V^{-1}s^{-1}$). Series resistances are not included here.

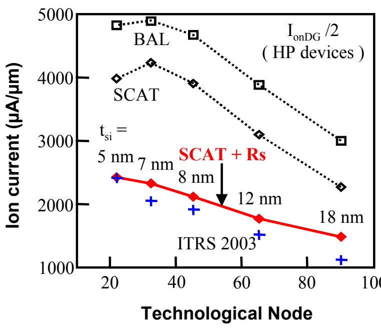

Fig 8 : Ion prediction using this model for High Performance devices (BAL = no scattering, SCAT = including scattering μ_{eff} = 310 - 270 $cm^2V^{-1}s^{-1}$, SCAT + Rs including series resistance). Gates are supposed to be metallic (no polydepletion) and the body thickness t_{si} used in the calculation is indicated. SCE and DIBL are not included.

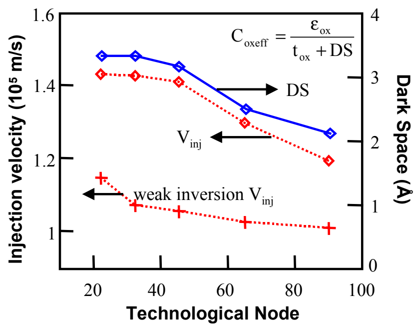

Fig 9 : Injection velocity prediction along the HP roadmap (at low drain voltage condition, in ballistic regime, with both low and high gate voltage) and Dark Space (extracted form the slope C_{oxeff} of the inversion charge V_g in strong inversion regime)