초박막형 전계효과 트랜지스터(UTB MOSFET)의 양자 국소화 효과에 의한 문턱전압 전이에 대한 컴팩트 모델링

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요약 초박막형 전계효과 트랜지스터(UTB MOSFET)의 양자 국소화 효과로 인해 발생하는 문턱전압 전이에 대한 이론적인 컴팩트 모델링을 연구하였다. UTB MOSFET 의 채널박막 두께가 나노미터 단위로 줄어듦에 따라 양자 국소화 효과로 인한 문턱전압의 전이를 심각하게 고려해야 한다. 채널 박막 두께 변화에 따른 문턱전압 전이를 선형 모양과 포물선 모양의 포텐셜 우물에서 섭동이론을 적용하여 해석적으로 모델화하였고, 그 결과를 채널 박막 두께가 4nm~8nm 인 UTB MOSFET 에서 얻은 실험 결과와 비교하여 잘 맞음을 확인하였다.

키워드: 초박막형 전계효과 트랜지스터, 문턱전압변화, 양자 국소화 효과

A Compact Modeling of Threshold Voltage Shift by a Quantum Confinement Effect in UTB MOSFET

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Abstract A compact modeling of threshold voltage shift by a quantum confinement effect in ultra-thin body (UTB) MOSFET is studied theoretically. As a body thickness of UTB MOSFET reduces into the nano-scale regime, the threshold voltage shift by the quantum confinement effect becomes a big concern. The threshold voltage shift as a function of the body thickness (T_{si}) is modeled analytically using perturbation theory for two types of potential well shape: linear and quadratic. Calculated data from the analytical model show a good agreement to the measured data from the fabricated UTB MOSFET in the range of body thickness from 4nm to 8nm.

Keyword: compact modeling, quantum confinement effect, threshold voltage shift, ultra-thin body (UTB) MOSFET, perturbation, and quantum well.

1. Introduction

A fully depleted silicon-on-insulator (SOI) MOSFET with an ultra-thin body has been considered as a promising device due to the overwhelming capability of short-channel effects (SCE) suppression and high performance [1]-[3].

In ultra-thin body (UTB) SOI MOSFETs, a quantum well is formed by a gate oxide, a conduction band of a silicon (NMOS), and a buried oxide in the SOI as shown in Fig. 2. In the heavily doped (> $10^{18}cm^{-3}$) body of a bulk-MOSFET, triangular (linear potential) shape of quantum well was formed [4][5]. The shape of potential well depends on a gate voltage, a body doping concentration (N_{body}), the buried oxide thickness, and the body thickness (T_{Si}) in the UTB MOSFETs. Quantum confinement starts to be significant when the body thickness is thinner than 10nm [6][7]. A quantum well causing the quantum confinement results in sub-band split as shown in Fig. 1. A conduction valley starts to be non-degenerate: 4-fold valley and 2-fold valley for NMOS. Similarly, a valence band starts to be non-degenerate: light-hole band and heavy-hole band for PMOS. As a body thickness scales down below sub-10nm, the sub-band spacing becomes greater than *kT* (26meV at 300°K). Thus, density of states (DOS) due to the quantum confinement decreases as the body thickness reduces, as shown in Fig. 2. It implies that an additional band bending is required to achieve the same amount of inversion charge per unit area [8]. As a result, the threshold voltage ($|V_t|$) increases as the body thickness decreases in both NMOS and PMOS. Experimental result already has proved this effect [4].

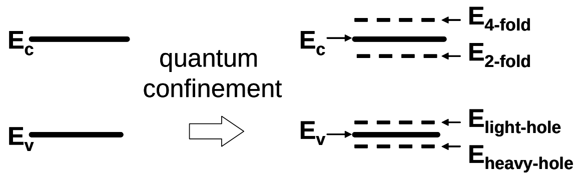

Fig. 1. Sub-bands start to be split in the conduction band and the valence band as the quantum confinement becomes significant.

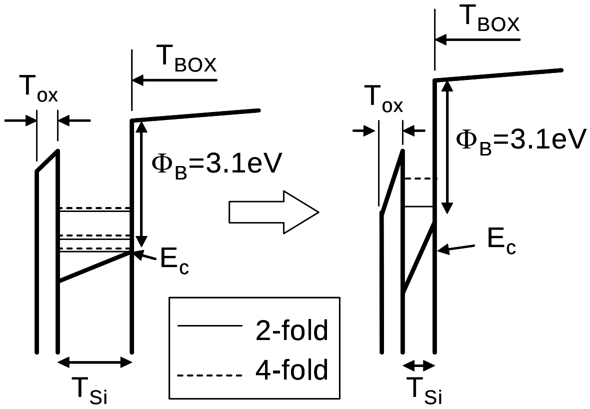

Fig. 2. As the body thickness decreases, allowable energy eigen-states decrease because of sub-bands split.

A previous work assumed that a shape of the potential well is close to a rectangle [9] for simple calculation. In this work, more realistic potential wells: a linear and a quadratic well are assumed and treated perturbatively with consideration of extra band bending as shown Fig. 3. It is found that newly proposed analytical model fits the measured data more accurately than the previous model.

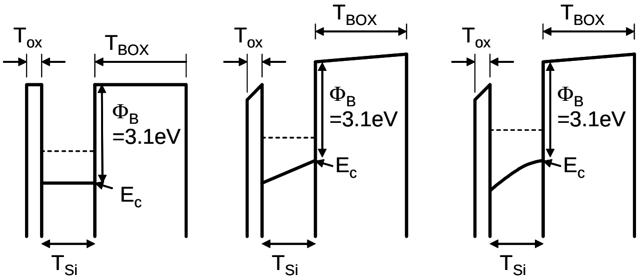

Fig 3. (a) Rectangular shape (b) Linear shape and (c) Quadratic shape potential well in UTB device.

2. Quantum Corrections with Perturbation Theory for Accurate Energy Eigen-States

Perturbation theory is a powerful method to correct energy eigen-states corresponding to a slight potential deformation [10]. When there is a small perturbation term (H') with an original Hamiltonian (corresponding to a rectangular type of potential), it can be treated perturbatively, then the corrected energy eigen-states are,

$$E_{correct} = E_n^0 + E_n^{\ 1} = E_n^0 + <\psi_n^{\ 0} \,|\, H' | \,\psi_n^{\ 0}> \quad \text{Eq. (1)}$$

Energy difference (Φ_B in Fig. 2) between the top of the band edge in the gate oxide and the conduction band edge, E_c is $3.1eV$. This energy difference, a depth of potential well, is assumed to be infinite to get simple eigen-functions. With comparison to the experimental data, this approximation is valid so far. Without perturbation potential (H'), the eigen-function in the infinite square well is expressed by

$$\psi_n^0(x) = \sqrt{\frac{2}{T_{Si}}}\sin\left(\frac{n\pi x}{T_{Si}}\right) \quad (n = 1,2,3...) \qquad \text{Eq. (2)}$$

The perturbed potential is now assumed to be expressed as a linear or a quadratic term. With assumption of the linear potential: $V(x)=bx$ $(b>0)$ and the quadratic potential: $V(x)=a(x^2-2xT_{si})$ $(a<0)$, the correction energies after calculation of $E_n^{\ 1}=<\psi_n^{\ 0}|H'|\psi_n^{\ 0}>$ for these two different potential shapes are respectively,

$$E_n(\text{linear}) = \frac{n^2\pi^2\hbar^2}{2m_{zi}T_{si}^{\ 2}} + \frac{b}{2}T_{si} \qquad \text{Eq. (3)}$$

$$E_n(\text{quadratic}) = \frac{n^2\pi^2\hbar^2}{2m_{zi}T_{si}^{\ 2}} - \frac{2}{3}aT_{si}^{\ 2} \qquad \text{Eq. (4)}$$

3. Inversion Charge Correction by Quantum Confinement

At room temperature, only the ground state from the bottom of the conduction band, E_c in the ultra-thin body devices is assumed to be occupied with majority carriers, electrons near the threshold condition in NMOS. This degenerated state splits into 2-fold valley (lowered) and 4-fold valley (raised). The ground energy state with consideration of sub-band split is incorporated into the proposed model.

The total inversion charge corrected by quantum confinement per unit area is expressed as

$$Q_i^{QM} = \frac{4\pi qkT}{h^2}(gm_d \sum_j \ln(1+e^{(E_f - E_c' - E_j)/kT}) + g'm_d' \sum_j \ln(1+e^{(E_f - E_c' - E_j)/kT})) \quad \text{Eq. (5)}$$

where g and g′ are the number of degeneracy, m_d and m_d' are the density of states effective masses, E_f-E_c' is the difference between the Fermi level and the bottom of the conduction band at the interface. Similarly, Q_i^{QM} can be calculated for PMOS with appropriate values of g_i and m_{di} as summarized in Table 1. Since sub-bands in valence band are coupled together, the treatment of PMOS as that of NMOS is not a right way. However, the proposed model fits the PMOS V_t shift as well even with the decoupling assumption.

		DOS Effective Mass(m_{di})	Degeneracy (g_i)
Conduction Band	2-fold valley	$0.19m_0$	2
	4-fold valley	$0.42m_0$	4
Valence Band	Light hole sub-band	$0.25m_0$	1
	Heavy hole sub-band	$0.65m_0$	1

Table 1. Effective mass and degeneracy for conduction and valence bands in (100) silicon.

In the counter part, the total inversion charge density by classical manner per unit area is expressed as

$$Q_i = \frac{kTn_i^2}{E_s N_{body}} e^{q\psi_s/kT} \quad \text{Eq. (6)}$$

where $E_s = qN_{body}T_{si}/\varepsilon_{si}$ is the electric field at the interface, and N_{body} is the doping concentration at the edge of the depletion layer. Therefore, the classical threshold condition, $\psi_s = 2\psi_B$, should be modified to $\psi_s = 2\psi_B + \Delta\psi_S^{QM}$. Plugging Eq. (5) and Eq. (6) into the following Eq. (7), we can get $\Delta\psi_S^{QM}$

$$\Delta\psi_s^{QM} = \frac{kT}{q}\ln\left(\frac{Q_i(\psi_s = 0)}{Q_i^{QM}(\psi_s = 0)}\right) \quad \text{Eq. (7)}$$

Assuming that only the ground state is occupied by electrons, approximated $\Delta\psi_S^{QM}$ is

$$\Delta\psi_s^{QM} \approx \frac{E_0}{q} - \frac{kT}{q}\ln\left(\frac{8\pi qm_d E_s}{h^2 N_c}\right) \quad \text{Eq. (8)}$$

For PMOS, N_c is simply replaced by N_v, and the sign and the effective mass in Eq. (8) is changed.

It is found that the ground energy state plays a crucial role to determine the surface potential change by the quantum confinement effect. The ground energy state is strongly influenced by the potential shape, which is corresponding to the perturbation potential.

4. Threshold Voltage Shift by Quantum Confinement Effect

The threshold voltage shift according to the perturbation potential is analytically calculated in NMOS and PMOS using Eq. (8),

$$\Delta V_t^{QM} = \frac{dV_g}{d\psi_s}\Delta\psi_s^{QM} = \left(1+\frac{3T_{ox}}{T_{si}}\right)\left[\pm\frac{E_0}{q} \mp \frac{kT}{q}\ln\left(\frac{8\pi qm_d E_s}{h^2 N_c}\right)\right] \quad \text{Eq. (9)}$$

Fig. 4 shows that the calculated data by the proposed model using Eq. (9) are matched with the experimental data. The calculated ΔV_t is obtained as ΔV_t^{QM} (thin body) - ΔV_t^{QM}(T_{si}=20nm) to compare with the measured data.

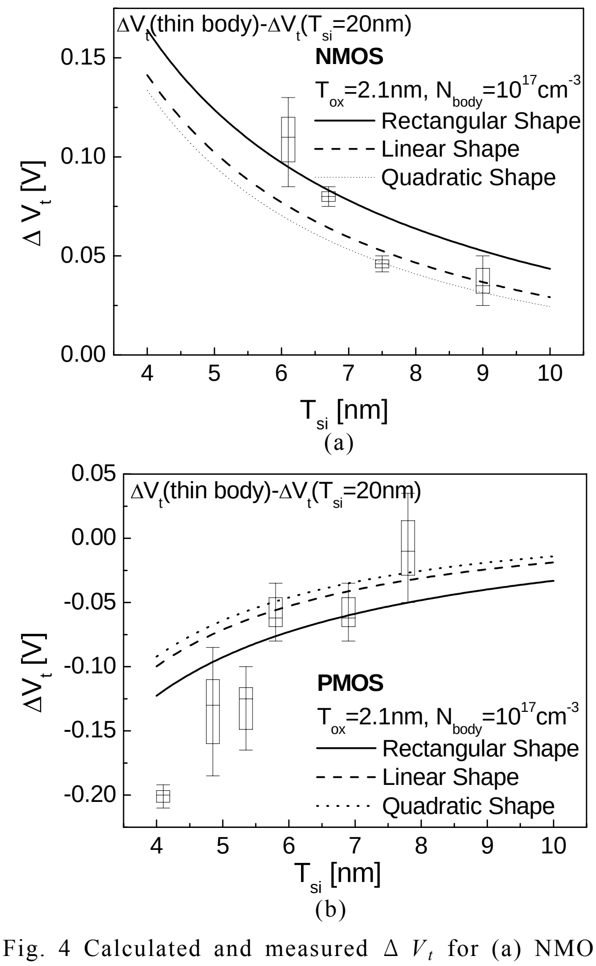

Fig. 4 Calculated and measured Δ V_t for (a) NMOS (b) PMOS as a function of T_{si} in proposed potential well models-Rectangular, Linear, and Quadratic Shapes.

As the body thickness decreases, the threshold voltage shift by the quantum confinement increases. This result is from the increment of the energy difference between E_0 and E_c and reduction of the density of states. The magnitude of the calculated ΔV_t^{QM} in the rectangular potential well is the smallest, however, the slope of rectangular type is steeper than the others. Therefore, the result shown in Fig. 4 is acceptable.

Fig. 5 shows that the threshold voltage shift by the quantum confinement effect in NMOS and PMOS depends on T_{si} and N_{body} for various shapes of potential well. It is larger in the quadratic potential well than in the linear and rectangular potential well because the ground energy state is bigger in the quadratic potential well than in the linear and rectangular potential well.

In terms of N_{body}, the surface electric field increases with increasing N_{body}. Thus, the threshold voltage shift decreases. ΔV_t is more sensitively dependent on T_{si} at low N_{body} than at high N_{body}.

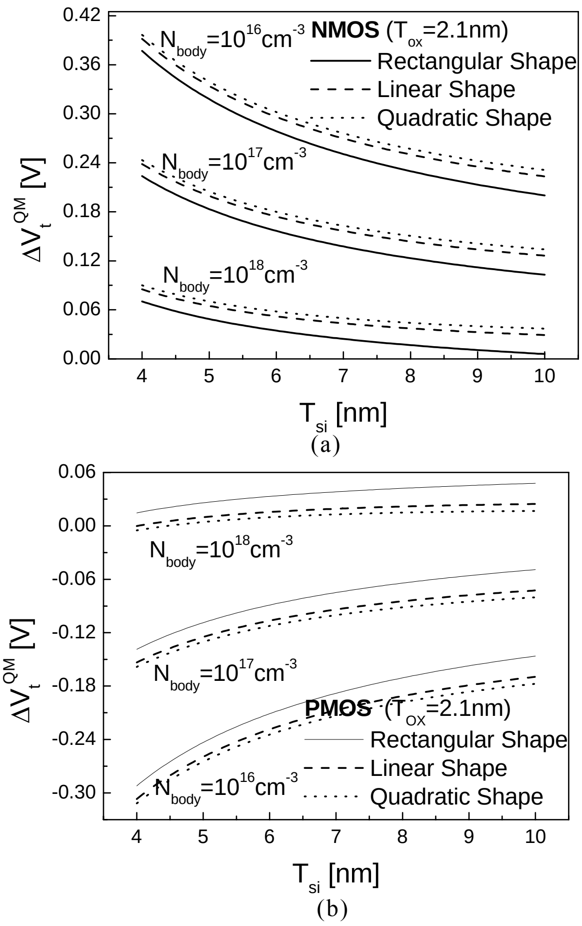

Fig. 5. ΔV_t^{QM} *vs*. T_{si} for various N_{body} and potential well shapes. (a) NMOS (b) PMOS

5. Conclusion

The analytical model to calculate the threshold voltage shift by a quantum confinement in UTB MOSFET is proposed with using perturbation theory for various potential wells: rectangular, linear, and quadratic. Its behavior is investigated for various T_{si} and N_{body}, and potential well shapes. It fits the experimental data very well. V_t shift by quantum confinement is significant when the body thickness is thinner than 5nm. V_t shift is larger in suggested linear and quadratic potential well model than in the previous rectangular potential well model, thus fits the experimental value at the extremely thin body accurately. Thus, the newly proposed compact model can predict an accurate V_t for a circuit simulation comprehensively

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