Origin of Drain-Current Oscillation on Ultra-Thin-SOI n-MOSFET

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Abstract

This is the first consistent simulation result to show that the quantization of carrier energy state in the channel is responsible for measured oscillations of the transconductance in scaled silicon-on-insulator (SOI) n-MOSFETs. Local changes in the Si layer thickness due to Si/SiO_2 interface roughness are already sufficient to shift the energy levels of these states.

1. Introduction

SOI MOSFETs with Separation by IMplanted OXygen (SIMOX) technology have been fabricated with the channel length down to 50 nm and a Si layer thickness of 6 nm[1]. Clear oscillations of the drain current I_D in the subthreshold region have been observed at low temperature. Additionally oscillations of g_m in the linear region as a function of the gate voltage V_G have been measured. In this paper we investigate the origin of the g_m oscillations. For this purpose a device simulation methodology is developed which solves the Schrödinger equation together with the Poisson equation consistently. We include not only the ground state but also the first excited electron energy level in the channel.

2. METHODOLOGY

2.1. Device Structure

Figure 1 shows measured I_D as a function of V_G together with the corresponding transconductance g_m values. Clear oscillations both in the subthreshold region and the linear region can be seen. Figure 2 shows (a) a cross section of the transistor and (b) an Atomic Force Microscope (AFM) picture of the buried oxide surface. The terrace step is about 0.5 nm height in average and the undulation period of about 50 nm.

The surface roughness is treated by two different geometries with different Si layer thicknesses, t_{si}. One is $t_{si} = 6\ nm$ (position A), the other is $t_{si} = 5\ nm$ (position B). The position A corresponds to the top of the terrace, and the other to the bottom.

Since the device is fabricated on the (001) surface, two series of subbands (longitudinal and transverse) are considered. In our simulation, image force and exchange-correlation effects are neglected[2].

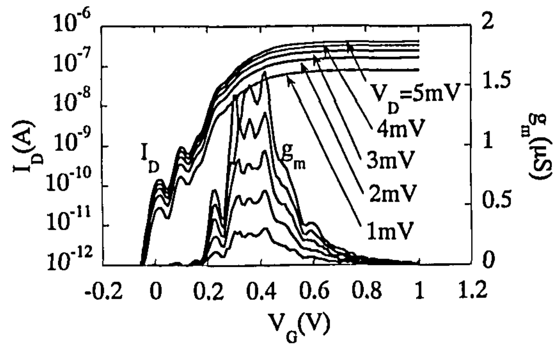

Figure 1: Measured I_D-V_G characterristics of SOI MOSFET together with their g_m values at $39K$ ($t_S = 6nm$ and $t_{OX} = 3nm$) for five different drain voltages. The channel length is 50 nm. The Si layer thickness and the gate oxide thickness are 6 nm and 3 nm, respectively.

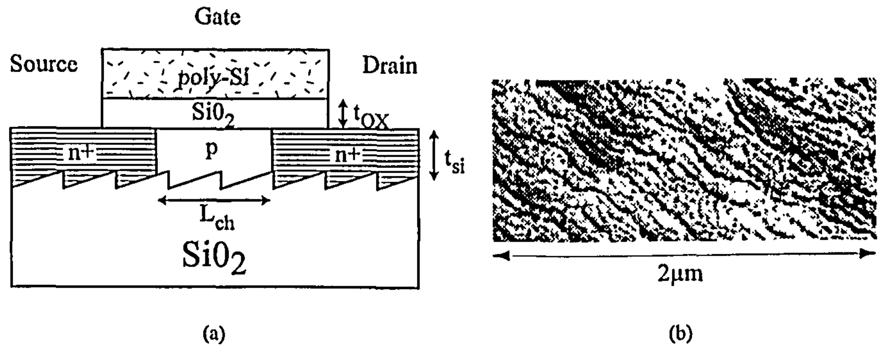

Figure 2: (a) Cross-section of SOI MOSFET, (b) an AFM picture of the buried oxide surface with the SIMOX technology. The surface at the Si/SiO_2 interface has the terrace structure. The mean value of the terrace height is about $0.5nm$.

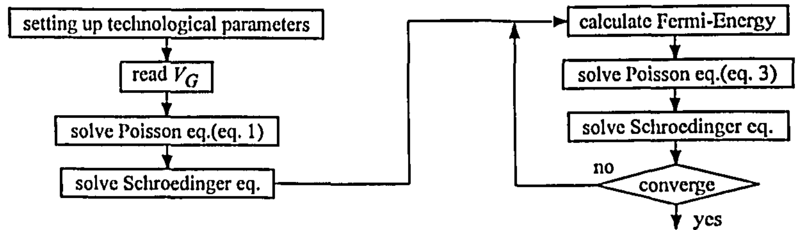

Figure 3: The flowchart of simulation procedure.

2.2. Self-Consistent Calculation

Figure 3 shows a flowchart of our simulation methodology. First, solve the conventional Poisson equation and Schrödinger equation with the potential ϕ derived from the Poisson equation. The next step is the self-consistent calculation solving the Poisson equation including the wave function ψ_{ij}

$$\frac{d^2\phi}{dx^2} = -\frac{1}{\epsilon_s}\left(\rho_{dep} - q\sum_{j=1}^{2}\sum_{i=0}^{\infty} N_{ij}\psi_{ij}^2\right) \tag{1}$$

and the Schrödinger equation together iteratively, where i and j are subband and valley indices, respectivery. The density of state N_{ij} is

$$N_{ij} = \frac{n_{vj} m_{dj} k_B T}{\pi \hbar^2} \ln\left\{1 + \exp\left(-\frac{E_F - E_{ij}}{k_B T}\right)\right\}, \tag{2}$$

where n_{vj} the degeneracy, m_{dj} the effective mass per valley, E_F Fermi-energy, $\hbar$ the reduced Planck constant, k_B the Boltzmann constant and T the absolute temperature[3].

2.3. Calculation of Transconductance

With use of energy level differences between the two cases, g_m oscillation is calculated. Since the ground-state energy at the position B is higher than that in the case A, carriers in the ground state at the position A have to overcome the built-in energy difference to enter the position B. The transmission probability T_r is described as[4]

$$T_r = \left|\frac{e^{-ik_1 d}}{\cos(k_2 d) + i(\epsilon/2)\sin(k_2 d)}\right|^2, \quad \epsilon = \frac{k_2}{k_1} + \frac{k_1}{k_2} \tag{3}$$

where k_1 and k_2 are the wave vector at the position A and B, and d is the width of the barrier, respectively. g_m is obtained after multiplying I_D by T_r. The parameter d is optimized so that g_m fits to the measurement.

3. SIMULATION RESULTS

Figure 4 show simulated energy states at two positions A and B in the channel. It can be seen that the energy level of the subbands of thin t_{si} are always higher than that of thick t_{si}. The difference is exactly responsible for the oscillation derived by Eq. (3).

Figure 5 shows calculated (a) T_r and (b) g_m as a function of V_G. From Fig. 5(a) it can be seen that the transmission of electrons at the ground state is responsible for the g_m oscillation for relative small V_G values. On the contrary, that for relative large V_G values is attributed to the transmission at the first-excited state. Figure 5(b) shows our calculated g_m as a function of V_G in comparison with measurements. A relative good agreement is achieved , where d is optimuzed to be 30 nm.

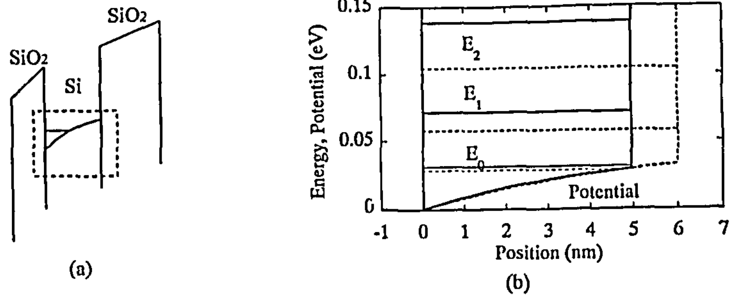

Figure 4: Band diagram (a) schematic and (b) simulated results for two different Si layer thicknesses. The solid lines correnpond to the position B and the dashed to the position A

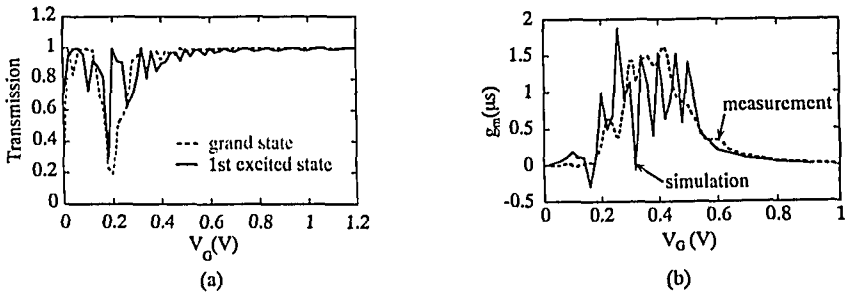

Figure 5: Calculated (a) T_r and (b) g_m as a function of V_G. The width of the potential barrier is optimized to be $30nm$.

References

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