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Weak Accumulation of Gate Polysilicon

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INTRODUCTION

To suppress depletion effect of gate polysilicon in MOSFETs, fully-silicided (FUSI) gate has been extensively studied these several years [1-3]. One of left fundamental issues is that capacitance of FUSI gate MOSFETs is larger than that of polygate MOSFETs having the same oxide thickness (T_{OX}) as the FUSI gate having in a case of negative gate voltage (V_G) [1, 3]. We regarded this difference as ascribed to weak accumulation layer (WAL), and then carried out the one-dimensional exact calculation. As a result, the measured CV characteristics of polygate and FUSI gate MOSFETs are excellently reproduced [4].

In this work, we will propose an approximation method to be implemented into general-use three-dimensional device simulators, and then discuss the influence of WAL on simulation of programming non-volatile memory cell.

WEAK ACCUMULATION [4]

The accumulation layer of polygate has been neglected since the band bending is quite small at the surface of degenerate polysilicon, assuming that the charge density is increased exponentially with the surface potential in terms of classical physics. However, expansion of electron wave is larger than width of accumulation layer which is too narrow for electrons to be confined there. Electrons are accordingly excited up to the three-dimensional conduction band at the surface. In this case, the density-of-states (DOS) becomes larger than in classical case (no accumulation layer) with a square-root function of surface potential (ψ_S), as shown in Fig. 1. To confirm this effect, we compare CV characteristics of the FUSI gate in which WAL can be neglected and the polygate including WAL, between the measurements and the exact calculation, as shown in Fig. 2. The excellent agreement strongly supports the WAL due the quantum repulsion effect. Since the CV characteristics are agreed between neglecting the WAL and considering it with 4Å thinner oxides, as shown in Fig. 3, the width of WAL is found to be 4Å.

METHOD and RESULTS

Considering that the DOS is increased in the square-root manner, we can solve the Poisson equation to obtain the surface charge density at the interface of polysilicon (Q_S):

$$Q_S = \alpha \times \varepsilon_F^{\ 1/2} \cdot \psi_S^{\ 3/4} \quad (1),$$

where ε_F is the Fermi energy calculated in the bulk of the polysilicon, considering many-body interactions of carrier-carrier and carrier-ion, incomplete ionization of donors and acceptors, and the Fermi-Dirac statistics [5, 6]. The increased density of electrons in WAL (δn_{QM}) is obtained:

$$\delta n_{QM} = \frac{\alpha^2}{2q^{3/2}\varepsilon_{Si}} \times \left\{ \sqrt{\varepsilon_F + q\psi} \cdot \varepsilon_F - \frac{\varepsilon_F^{\ 2}}{\sqrt{\varepsilon_F + q\psi}} \right\} \quad (2),$$

where ψ is a local potential in the WAL, ε_{Si} is the silicon permittivity and q is the elementary charge. The α can be written as a function of polysilicon material constants (the effective density-of-states mass, the permittivity, and the number of conduction valleys). However, since these constants are ambiguous as long as considering the influence of grains in polysilicon, we may regard α as a fitting parameter. To extract α, we compare Q_S and ψ_S that are calculated using Eqs. (1) and (2), and are exactly calculated while the donor density in polysilicon (N_D) is $1\times10^{20}\text{cm}^{-3}$, as shown in Fig. 4. The agreement is obtained if we set $\alpha=1\times10^5(\text{C}^{1/2}\text{V}^{-5/4}\text{cm}^{-2})$, while the classical calculation gives us the overestimated Q_S and the underestimated ψ_S. The CV characteristics are agreed using the same value of α regardless of T_{OX}, as shown in Fig. 5, which indicates that α is independent of T_{OX}. On the other hand, the extracted α is decreased as N_D is increased, as shown in Fig. 6. This is due to the decrease of WAL width.

DISCUSSION

The present method is applicable to simulation of programming non-volatile memory, since WAL appears at the interface between floating gate (FG) and inter-poly dielectric (IPD) film. Note that Ψ_S degrades the tunnel barrier height (ϕ_B) although electric field across the IPD layer (E_{IPD}) is unchanged. This increases the tunneling from FG to traps in IPD film and from the traps to control gate, which degrades the programming efficiency. Then, if the WAL was neglected, then the tunnel mass of the IPD film would be increased from that of the tunnel oxide film by:

$$1 + 3q\psi_S \cdot \frac{\phi_B^{\ 1/2} - (\phi_B - E_{IPD} \cdot T_{IPD})^{1/2}}{\phi_B^{\ 3/2} - (\phi_B - E_{IPD} \cdot T_{IPD})^{3/2}},$$

where T_{IPD} is the IPD thickness, and ϕ_B is the barrier height. Since this increase of tunnel mass causes the calibration to be complicated, the present method using Eqs. (1) and (2) is quite useful.

CONCLUSION

An approximation method for calculating the effect of WAL is proposed. The influence of the WAL on simulation of programming non-volatile memory is discussed.

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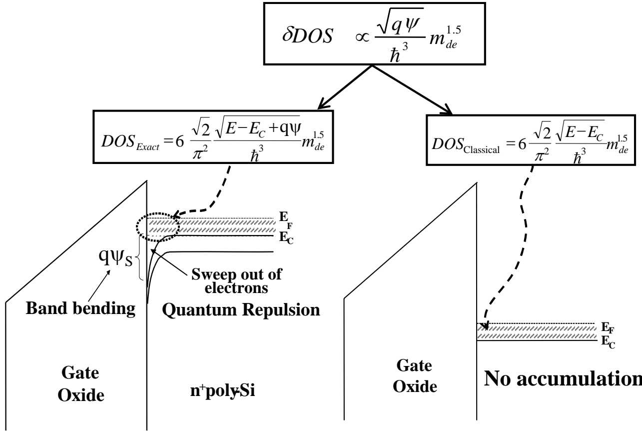

Fig. 1 Scheme of the weak accumulation: The m_{de} is the effective density-of-states mass of electron in polysilicon

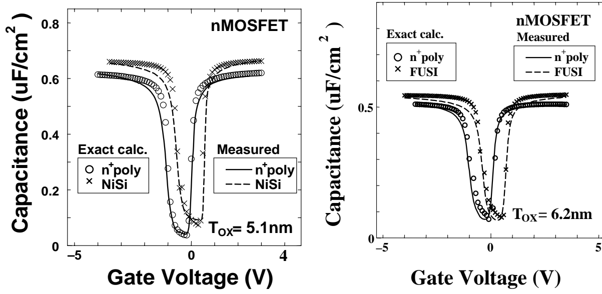

Fig. 2 Exact calculation and measurement of CV characteristics: The oxide thicknesses of the FUSI gate and the polygate MOSFETs are regarded as equivalent, since the same processes were carried out before fabricating the gates [4].

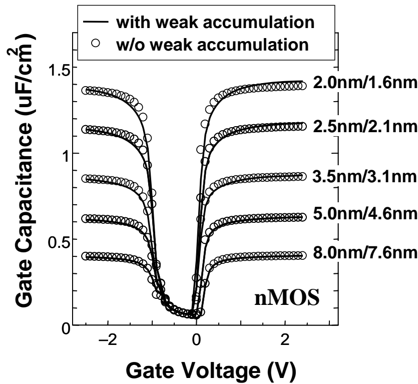

Fig. 3 CV characteristics calculated neglecting the polysilicon band bending (i.e., neglecting both WAL and incomplete depletion layer [6]) and considering it with 4Å thinner oxides, while N_D is fixed $1\times10^{20}\text{cm}^{-3}$. The width of WAL and the incomplete depletion layer are almost same.

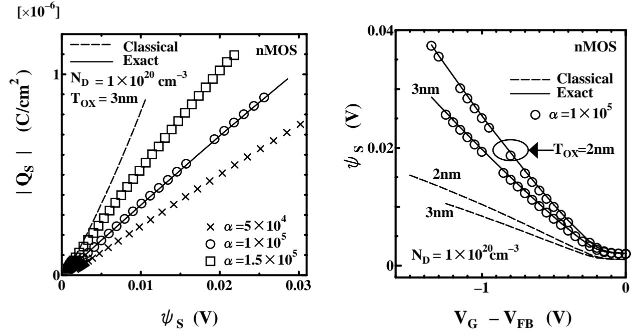

Fig. 4 Calculated surface charge density and surface potential: The dashed line depicts the data classically calculated neglecting the weak accumulation. The bulk line depicts the data exactly calculated considering the weak accumulation. The marks (circles) depict the present data calculated using Eqs. (1) and (2). Not-converged data are removed. The present and the exact data are excellently agreed in both figures while the classical calculation gives us the overestimated Q_S and the underestimated ψ_S. The V_{FB} is flat band potential. The unit of α is $(C^{1/2}V^{-5/4}\text{cm}^{-2})$.

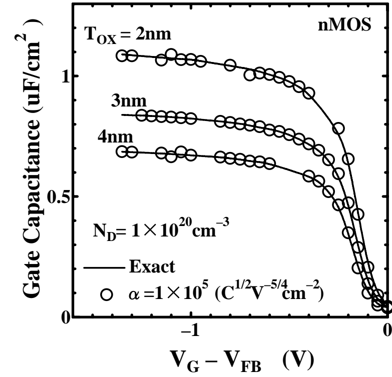

Fig. 5 Calculated CV characteristics: The bulk line depicts the data exactly calculated considering the weak accumulation. The marks (circles) depict the present data calculated using Eqs. (1) and (2) and $\alpha=1\times10^5(C^{1/2}V^{-5/4}\text{cm}^{-2})$. Not-converged data are removed. The V_{FB} is flat band potential. The present and the exact data are excellently agreed regardless of T_{OX} while N_D is $1\times10^{20}\text{cm}^{-3}$.

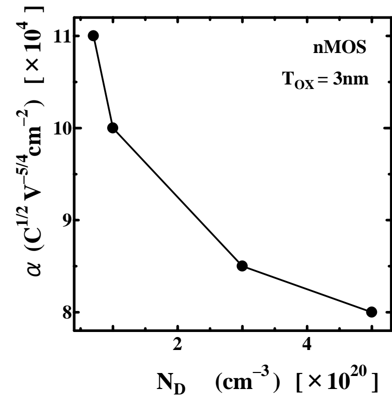

Fig. 6 The extracted α: The value of α is decreased as N_D is increased, since the WAL width is decreased with the increase of N_D while ψ_S is fixed.