MOBILITY MODELING IN SOI FETS FOR DIFFERENT SUBSTRATE ORIENTATIONS AND STRAIN CONDITIONS

SHORT TITLE: MOBILITY MODELING IN SOI FETs

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Abstract. Conduction band modification due to shear stress is investigated. Mobility in single- and double-gate SOI FETs is modeled for Silicon thin body orientation (001) and (110) under general stress conditions. Decrease of conductivity mass induced by uniaxial [110] tensile stress leads to mobility enhancement in the stress direction in ultra-thin body SOI MOSFETs.

Keywords: mobility modeling, Monte Carlo simulations, SOI FET, stress engineering, hybrid orientation

1. Introduction

Mobility in ultra-thin body (UTB) FETs in double-gate (DG) and single-gate (SG) configuration has recently been the subject of intensive experimental[1,2] and theoretical[3,4] studies. Mobility in DG devices is expected to be enhanced as compared to the mobility in SG FETs due to volume inversion[5]. Recent experiments[2] have confirmed that the DG mobility is indeed higher than the SG mobility in (110) UTB FETs in the whole range of inversion charge concentrations. Contrary to predictions of volume inversion hypothesis[5], however, the mobility in (100) UTB DG FETs is lower than the SG mobility at high carrier concentrations[1,2]. In order to resolve the apparent controversy, an accurate mobility modeling in UTB FETs is required for different substrate orientations, both in DG and

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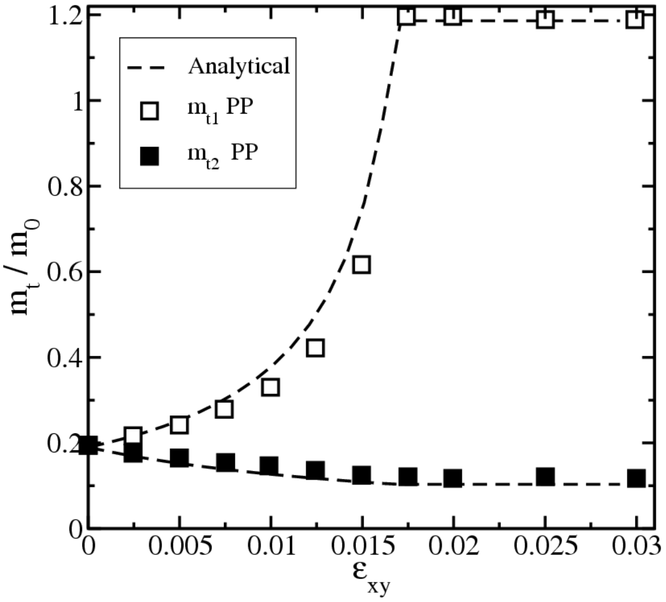

Figure 1. Transversal mass changes in valleys along the [001] axis as a function of the shear component of the strain tensor due to uniaxial [110] tensile stress. Results of the empirical pseudopotential method (symbols) are compared to Eq. (1) (dashed lines). Closed squares describe the conductivity mass reduction in the [110] tensile stress direction.

SG structures. Additional process steps to induce uniaxial strain along the MOSFET channel have recently become routinely used by the semiconductor industry. Surprisingly, stress along [110] has received little attention within the research community. Only recently a systematic experimental study of the mobility modification due to stress in [110] was reported[6]. It was demonstrated that the electron mobility data under [110] stress condition is consistent with the conductivity mass being a function of the stress value. Since stress engineering is becoming an established technique to enhance performance of modern MOSFETs, it is important to include appropriate models into modern simulation tools.

2. Uniaxial stress and conduction band structure

The [110] stress produces off-diagonal elements ε_{xy} in the strain tensor, which lift the degeneracy between the two lowest conduction bands at the *X* points along the [001] axis in the Brillouin zone[7]. Because of that the conduction band minimum moves closer to the *X* point, and shifts down in energy with respect to the four remaining degenerate valleys. Uniaxial stress also modifies longitudinal and transversal effective masses in the

[001] valleys. Results of simulations of the transversal mass dependences on tensile stress in [110] direction using empirical pseudopotential method[8] are shown in Fig.1, together with analytical expressions

$$m_t(\eta)/m_t = \left[1 \pm \eta\, m_t / M\right]^{-1}, \qquad |\eta| \le 1; \qquad \text{(1a)}$$

$$m_t(\eta)/m_t = \left[1 \pm m_t / M\right]^{-1}, \qquad |\eta| \ge 1, \qquad \text{(1b)}$$

where $\eta = 2D\varepsilon_{xy}/\Delta$, Δ is the conduction band splitting at the minimum in unstrained Si, and D is the shear deformation potential, and $M = m_0/4.4$ is a parameter. The sign "+" corresponds to the mass decrease along the [110] stress direction, while the sign "-" – in [-110] direction.

3. Method

We have used a subband Monte Carlo algorithm to compute the electron mobility in thin silicon films. The algorithm includes degeneracy effects[9], which are of major importance in UTB FETs, especially at high effective fields. We included electron-phonon and surface roughness scattering. The surface roughness is assumed uncorrelated and equal at opposite UTB film interfaces.

4. Results

Fig.2 shows the mobility calculated in a thick silicon film for (100) and (110) substrate orientations. For a 20 nm thick film the mobility in SG mode coincides with the DG mobility, plotted as function of the concentration per channel. Mobility is isotropic for (100) substrate orientation, whereas for (110) a clear anisotropy is displayed. Results of simulations are in good agreement with the experimental data[1,2] also shown in Fig. 2.

We apply uniaxial strain of 0.1 GPa and 1.0 GPa along [110] direction to a thick (001) oriented Si film. Fig.3 demonstrates that the in-plane mobility enhancement is maximal along the strain direction. In the in-plane direction orthogonal to strain the mobility enhancement is less pronounced and may change sign depending on carrier concentration. The enhancement is clearly anisotropic. Similar anisotropic mobility enhancement under [110] uniaxial stress was recently observed experimentally[10]. This anisotropy cannot be explained by the higher subband depopulation due to strain since the ground subband is isotropic, which would inevitably result in isotropic mobility. Therefore, the anisotropic mobility enhancement is due to conductivity mass anisotropy produced by [110] strain as illustrated in Fig.1.

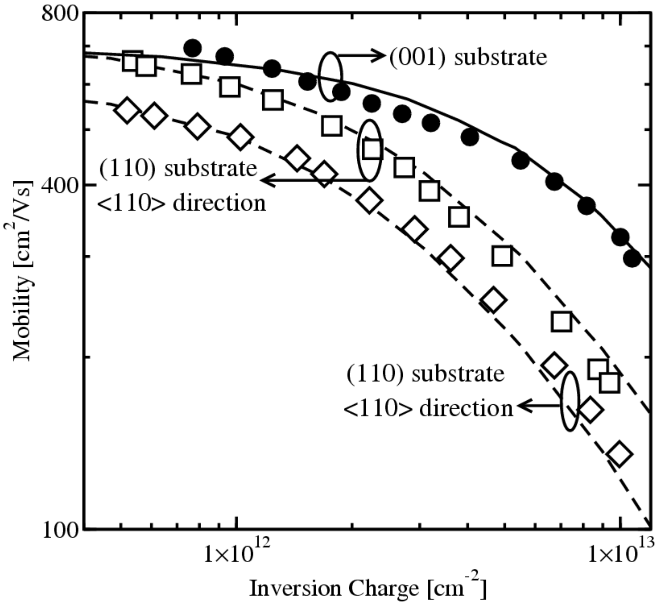

Figure 2. Simulated mobility for a 20 nm thick Si body compared to measurements [1,2] (symbols), for (110) and (110) substrate orientation.

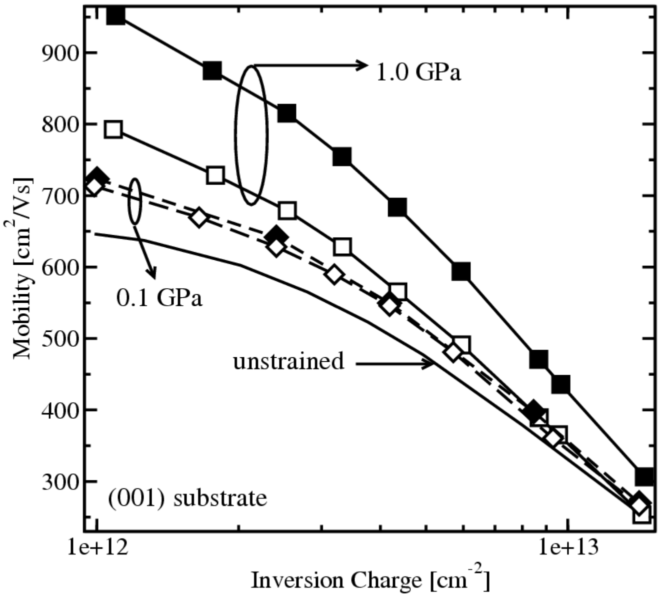

Figure 3. Channel mobility enhancement in 20 nm thick (100) Si film for two values of uniaxial stress along [110].

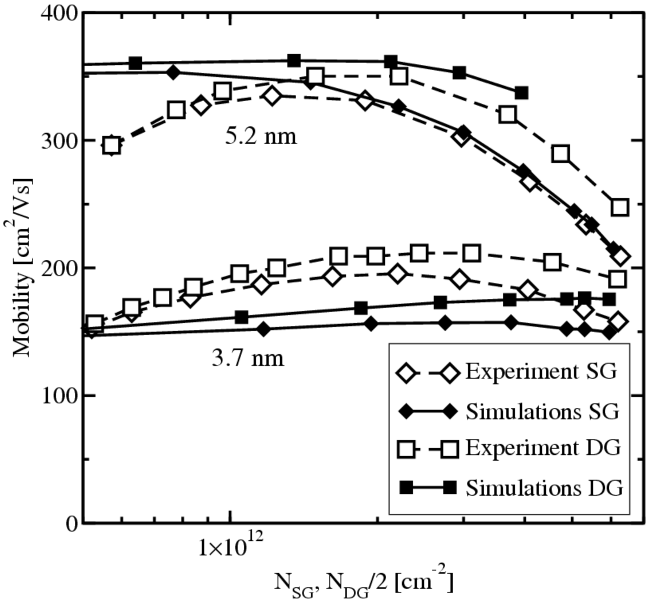

Figure 4. Mobility for (110) substrate in <001> direction, for different silicon body thicknesses. Mobility in DG operation is higher for all N_S, in qualitative agreement with recent experiments[2].

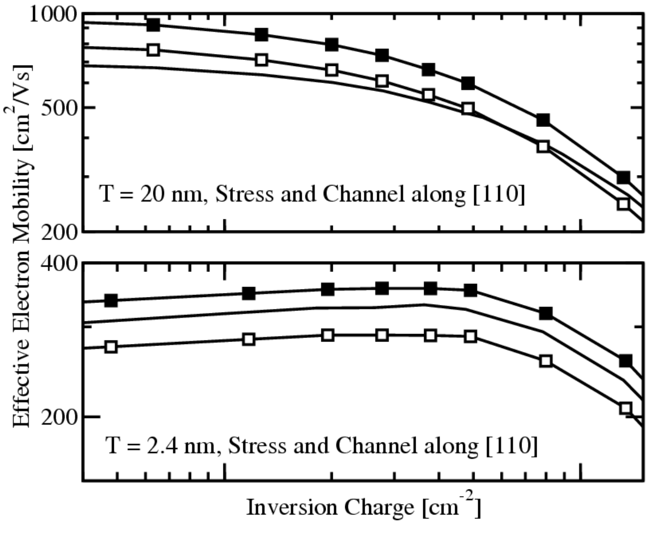

Figure 5. Mobility for [110] uniaxial stress in (001) UTB Si films. Substantial mobility modification for 2.4 nm UTB thickness is due to the effective mass change.

Mobility dependences on charge concentration for (110) substrate are shown in Fig. 4. Mobility, which is anisotropic, is only shown in <001> direction, for different silicon thicknesses. Due to volume inversion[5] the mobility in DG operation is higher for all N_S than the SG mobility, in good agreement with experimental data[2]. Finally, we study the influence of strain on UTB FET mobility. Results of mobility calculations for [110] uniaxial stress are shown in Fig. 5 for two (001) oriented Si body thicknesses. Due to the change of the effective masses (Fig. 1) induced by strain a substantial in-plane mobility modulation is observed even at 2.4 nm thick Si film. Uniaxial stress is a promising technique for mobility engineering in UTB FETs.

5. Conclusion

Effective mass dependences on the strength of uniaxial [110] stress in the valleys along the [001] direction are analyzed both theoretically and computationally using the empirical pseudopotential method. Mobility in single- and double-gate SOI FETs is modeled for different Si thin body orientation under general stress conditions. Good agreement with recent experiment is found for ultra-thin body (110) orientated FETs. It is shown that uniaxial [110] tensile stress reduces the conductivity mass and leads to mobility enhancement in the stress direction in ultra-thin body SOIFETs.

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