Subband Parameters in Strained (110) Silicon Films from the Hensel-Hasegawa-Nakayama Model of the Conduction Band

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FinFETs are considered good candidates for the 22nm technology node and beyond. In addition to two (001) interfaces, the [110] oriented FinFETs possess two (-110) inversion channels. In the parabolic approximation of the conduction band the electronic structure in surface layers at the (-110) interfaces is characterized by two sets of subband ladders [1]. There is growing experimental evidence [2], [3], however, that the parabolic approximation is not sufficient to accurately describe the subband parameters (effective masses and subband energies) in ultra-thin films under uniaxial stress. For instance, the effective masses of the unprimed subbands in a (001) film depend on shear strain [2] and silicon film thickness [4], as shown in Fig.1. These effects are ignored in the parabolic band approximation but well described by the Hensel-Hasegawa-Nakayama (HHN) model [5] of the conduction band.

In this work we demonstrate that the HHN model allows to accurately describe the dependences of the subband energies and effective masses in (-110) thin silicon films. In order to do so, we appropriately rotate the HHN Hamiltonian [5] for each pair of the valleys and resolve the subband structure numerically. The zero boundary conditions for the wave functions at the interfaces are applied. Fig.2 demonstrates the thickness dependence of the effective mass of the ground unprimed subbands of (-110) films in the [010] direction. Results are in agreement with those obtained by the pseudo-potential method [6]. The effective mass increase indicates that transport properties in ultra-thin (-110) films in [010] direction are degraded with decreasing thickness t.

Fig.3 shows the subband energy dependence of the film thickness for the lowest primed and unprimed subbands. Surprisingly, in ultra-thin (-110) films the two-fold degenerate subband becomes lower in energy than the four-fold degenerate one. This is a direct manifestation of the increased non-parabolicity [3] of the [001] valleys in the [110] quantization direction. The two-fold degenerate subbands are characterized by the lighter mass m_t in [110] direction. Thus, the [110] channel direction becomes beneficial in FinFETs with ultra-thin bodies. Analytical results for the two-fold degenerate subbands also shown in Fig.3 are obtained by substituting k_x by its quantized values $\pi n / t$ in the dispersion

$$E = \hbar^2 / 2m_l \left(k_z^2 + m_l / m_t \left(k_x^2 + k_y^2\right) - 2\sqrt{k_0^2 k_z^2 + (m_l D\varepsilon_{xy} / \hbar^2 + m_l (k_x^2 - k_y^2) / M)^2}\right), \quad (1)$$

where $k_0 = 0.15 \times 2\pi / a$, $M^{-1} \approx m_t^{-1} - m_0^{-1}$, ε_{xy} denotes the shear strain component, and D=14 eV is the shear strain deformation potential, while for the four-fold degenerate subbands the energy

$$E_n = \hbar^2 \pi^2 n^2 (m_l + m_t) / (4 m_l m_t t^2) \quad (2)$$

with the corresponding quantization mass [1] is used. Fig.4 demonstrates that (1) describes accurately not only the minimum position but also the dispersion in [110] k_y direction of the two-fold degenerate unprimed subbands in a t=3nm thin relaxed film.

Tensile uniaxial stress along the channel enhances electron transport in [110] direction. In a (-110) thin film the uniaxial stress alters the relative position of primed and unprimed subband ladders. Due to an increase of the quantization mass m_x in the [-110] direction for increased tensile ε_{xy} and higher non-parabolicity at reduced thicknesses this transition happens at low stress values as compared to the case when these effects are ignored ($1/M$=0), as shown in Fig.5. The effective mass in the transport direction is, however, reduced with increased stress and decreased thickness t as demonstrated in Fig.6. Thus, we conclude that FinFETs with ultra-thin body tensely stressed along the [110] channel have superior transport characteristics over [010] FinFETs because of the subband ladders' inversion and a lighter effective mass of the lowest subband.

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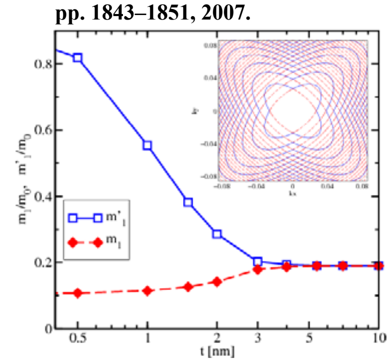

Fig.1 Effective mass dependence on thickness for the two unprimed ground subbands in a (001) film. Inset: subband dispersions in a film with t=1.36nm.

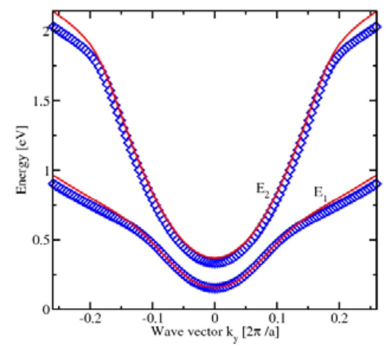

Fig.4 Two-fold degenerate subband dispersion in the [110] direction for a (-110) film with t=3nm. Lines are obtained with (1).

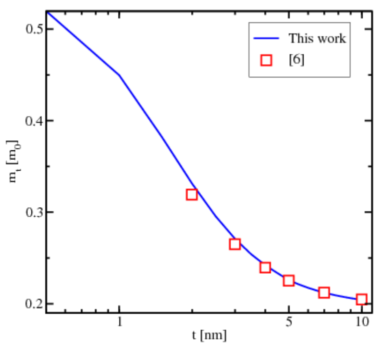

Fig.2 [010] effective mass dependence on thickness for the four-fold degenerate ground subband in a (-110) film. Results of our work are compared to [6].

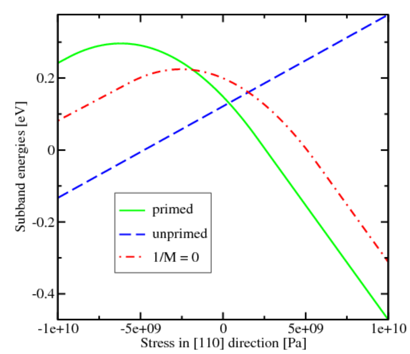

Fig.5 Crossing between the first primed and unprimed subbands in a t=3nm (-110) film as a function of uniaxial stress in [110] direction.

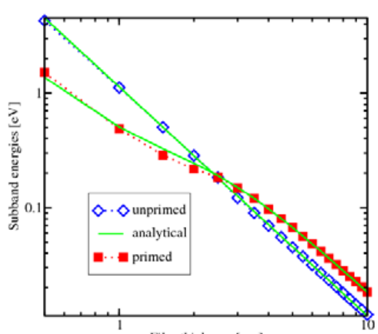

Fig.3 Dependence of the primed and unprimed subband energies on t in (-110) films. Analytical results (1) and (2) are shown by lines.

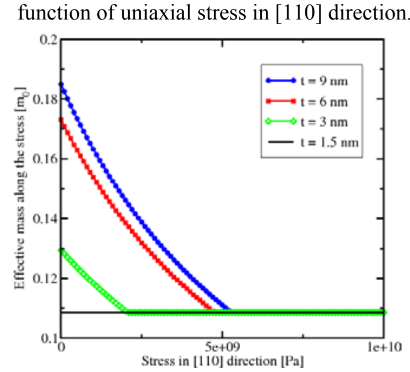

Fig.6 Dependence of the transport effective mass in the first two-fold degenerate subbands on tensile stress along the [110] channel, for several thicknesses of (-110) films.