Low-Field Mobility in Strained Silicon Inversion Layers and UTB MOSFETs for Different Substrate Orientations

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Abstract. To continue improvement of CMOS device performance process induced uniaxial stress is widely adopted in logic technologies starting from the 90 nm technology generation. In this work we model stress induced electron mobility enhancement in ultra thin body (UTB) MOSFETs for (001) and (110) substrate orientation using the Monte Carlo method. Uniaxial stress effects on the band structure are incorporated by adapting the non-local empirical pseudopotential method including spin-orbit interaction for arbitrary strain conditions. Stress induced change of the electron effective mass is found to be very important to explain mobility enhancement in UTB MOSFETs. Simulation results of electron mobility are in good agreement to recent experimental data.

Keywords: Monte Carlo method, uniaxial strain/stress, low-field mobility
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SIMULATION METHOD

Theoretical modeling of strain induced mobility enhancement for electrons and holes is an important issue with some critical questions still open [1, 2]. For this reason a simplified approach based on the empirically measured piezoresistance coefficients is often used by industry to predict mobility enhancement for electrons and holes.

In this work we analyze electron mobility enhancement by solving the Boltzmann equation using a MC method. The band structure of Si was calculated using the non-local empirical pseudopotential method (EPM) including spin-orbit coupling [3]. The effective masses were extracted from the curvature of the conduction bands at the minima along various directions and have been incorporated in the transport calculations. When the strain tensor in the crystal system contains off-diagonal components, a pronounced electron effective mass change is observed. Under $\langle 110\rangle$ stress the constant energy surfaces of the two-fold degenerate Δ_2-valleys take the form of scalene ellipsoids $(m_l, m_{t,||}, m_{t,\perp})$, where $m_{t,||}$ and $m_{t,\perp}$ denote the transverse mass parallel and perpendicular to the stress direction. Band structure simulations indicate that uniaxial tensile stress along $\langle 110\rangle$ decreases $m_{t,||}$ with respect to $m_{t,\perp}$. Analytical fits characterizing the changes of $m_l, m_{t,||}$, and $m_{t,\perp}$ as a function of applied $\langle 110\rangle$ stress are reported in [3]. The observed effective mass change is consistent with a theoretical result in [4] and is in good agreement with a recently reported study [5].

The subband structure of the two dimensional electron gas was calculated using a one-dimensional Schrödinger-Poisson solver with modifications to account for the strain induced energy splitting between the subband ladders. Transport calculations have accounted for electron-phonon interaction and surface roughness scattering. The Monte Carlo method used for this work is based on the solution of the linearized Boltzmann equation and allows the exact treatment of the Pauli exclusion principle in the limit of vanishing driving fields.

MOBILITY IN UTB MOSFETS

In Si inversion layers the six-fold degenerate Δ_6 valley splits into up to three different subband ladders depending on the orientation of the substrate. For (001) substrate the masses of the lowest (unprimed) subband ladders are spherical and that the ladders are two-fold degenerate. On (110) substrate the masses of the unprimed subband ladders are anisotropic and the ladders are four-fold degenerate. The higher density of states and larger transport masses on (110) substrate yield a lower inversion layer mobility as compared to (001) substrate.

On (001) substrate the mobility can be enhanced if stress direction and channel direction are both [110]. The reasons are the stress induced valley splitting and the stress induced effective mass change. At relatively large body thicknesses, e.g. T_{SOI}=20 nm, $\Delta\mu_{\mathrm{eff}}$ can be understood from a combination of the two effects yielding an anisotropic μ_{eff} as compared to the unstressed system (see Fig. 1).

In ultra-thin Si bodies, however, the strong quantum confinement induces a large intrinsic valley splitting, thus stress induced valley shifts have a negligible effect on the mobility. At T_{SOI}=2.4 nm, the larger (smaller) component of the mobility parallel (perpendicular) to the stress direction [110] results from the effective mass

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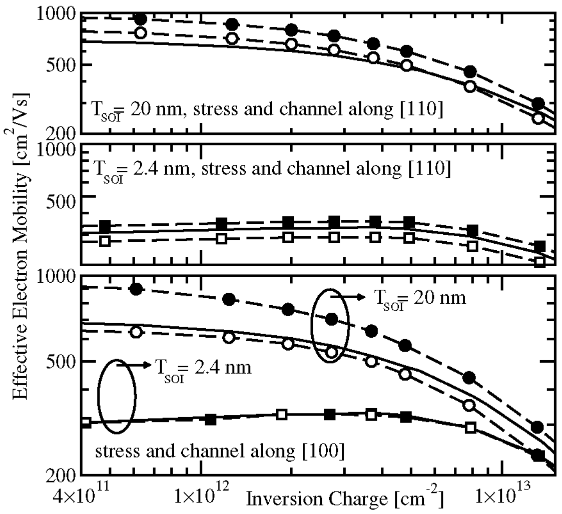

FIGURE 1. Simulated effective mobility for substrate orientation (001), two channel orientations and two body thicknesses of unstressed (solid lines) and 1 GPa stressed Si (dashed lines). The mobilities are plotted parallel (closed symbols) and perpendicular (open symbols) to the stress direction.

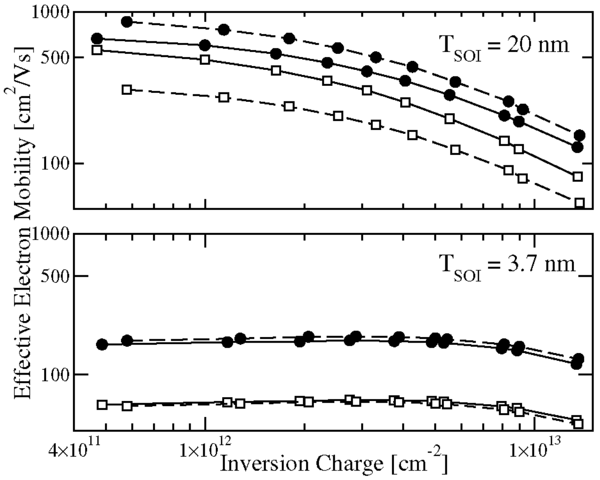

FIGURE 2. Simulated effective mobility for substrate orientation (110) of unstressed (solid lines) and 1 GPa stressed (dashed lines) Si for two body thicknesses. The mobility components are plotted parallel (closed symbols) and perpendicular (open symbols) to stress direction [001].

change only and is found in good agreement with experimental data [5]. Additionally, in Fig. 1 the effect of uniaxial stress on the mobility with channel direction and stress direction parallel to [100] is shown. The effect of uniaxial tensile stress is qualitatively different from wafers with stress and channel along [110]. Stress along [100] lifts the degeneracy of the fourfold (primed) ladder. Since effective mass does not change, mobility enhancement is only observed at large T_{SOI} and is a result of subband ladder splitting only.

Stress induced $\Delta\mu_{\mathrm{eff}}$ on (110) oriented substrates can be understood from similar arguments. Tensile stress along [001] does not alter the mobility at small T_{SOI}, because it does not change the effective masses, but merely increases the splitting between the primed and unprimed subband ladders. Fig. 2 shows that the stress induced mobility enhancement, observed at $T_{\mathrm{SOI}} = 20.0\,\mathrm{nm}$, vanishes at $T_{\mathrm{SOI}} = 3.7\,\mathrm{nm}$.

CONCLUSION

The effect of uniaxial stress on the electron mobility was analyzed by means of MC simulations. Experimentally observed mobility data were reproduced for bulk Si and Si inversion layers on (001) and (110) oriented substrates with large and small body thicknesses. Mobility enhancement can be understood only from a combination of three effects: (i) subband ladder repopulation, (ii) change in inter-subband scattering, and (iii) stress induced effective mass changes. While repopulation effects can increase the bulk and inversion layer mobilities at relatively large body thicknesses ($T_{\mathrm{SOI}} > 20\,\mathrm{nm}$), the population of higher subband ladders is intrinsically reduced by strong quantum confinement for very small body thickness ($T_{\mathrm{SOI}} < 5\,\mathrm{nm}$). Thus, in the latter case, no mobility enhancement can be expected from stress induced repopulation effects and only the stress induced effective mass change can explain the experimentally observed mobility enhancement. In this aspect, stress conditions reducing the effective mass in transport direction (like uniaxial tensile stress along $\langle 110\rangle$) are very beneficial to increase mobility in UTB-MOSFETs.

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REFERENCES

1. M. V. Fischetti, F. Gamiz, and W. Hänsch, *J.Appl.Phys.* **92**, 7320–7324 (2002).
2. M. V. Fischetti, and Z. Ren, *J.Appl.Phys.* **94**, 1079–1095 (2003).
3. E. Ungersboeck, S. Dhar, G. Karlowatz, H. Kosina, and S. Selberherr, "Physical Modeling of Electron Mobility Enhancement for Arbitrarily Strained Silicon," in *11th International Workshop on Computational Electronics Book of Abstracts*, 2006, pp. 141–142.
4. G. L. Bir, and G. E. Pikus, *Symmetry and Strain Induced Effects in Semiconductors*, Wiley, New York, 1974.
5. K. Uchida, T. Krishnamohan, K. Saraswat, and Y.Nishis, "Physical Mechanisms of Electron Mobility Enhancement in Uniaxial Stressed MOSFETs and Impact of Uniaxial Stress Engineering in Ballistic Regime," in *Proc. Intl. Electron Device Meeting*, 2005, pp. 135–138.