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# High performance, uniaxially-strained, silicon and germanium, double-gate p-MOSFETs

T. Krishnamohan [a,e,*], C. Jungemann [b], D. Kim [a], E. Ungersboeck [c], S. Selberherr [c], A.-T. Pham [d], B. Meinerzhagen [d], P. Wong [a], Y. Nishi [a], K. C. Saraswat [a]

[a] *Department of Electrical Engineering, Stanford University, Stanford, CA, USA 94305*
[b] *University of the Armed Forces, Munich, Germany*
[c] *Institute for Microelectronics, TU Wien, Vienna, Austria*
[d] *Technical University of Braunschweig, Germany*
[e] *Intel Corporation, Santa Clara, CA, USA*

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## Abstract

The effect of uniaxial-strain, band-structure, mobility, effective masses, density of states, channel orientation and high-field transport on the drive current, off-state leakage and switching delay in nano-scale, Silicon (Si) and Germanium (Ge), p-MOS DGFETs is thoroughly and systematically investigated. To accurately model and capture all these complex effects, different simulation techniques, such as the Non-local Empirical Pseudopotential method (bandstructure), Full-Band Monte-Carlo Simulations (transport), 1-D Poisson-Schrodinger (electrostatics) and detailed Band-To-Band-Tunneling (BTBT) (including bandstructure and quantum effects) simulations, were used in this study.

*Keywords*: Uniaxial strain, Strained silicon, Strained germanium, Double-gate MOSFETs, Monte Carlo, Band To Band Tunneling,

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## 1. Introduction

Currently, uniaxial compressively strained Si is the dominant technology for high performance p-MOSFETs and increasing the strain provides a viable solution to scaling [1]. However, looking into future nanoscale p-MOSFETs, it is important to examine novel higher mobility channel materials, like Ge, strained-SiGe or strained-Ge, which may perform better than even very highly strained-Si [2]-[5]. Previous work has attempted to explain the transport in uniaxial strained-Si MOSFETs through simple bandstructure and mobility calculations. However, as we scale MOSFETs down to very short channel lengths, the effect of the high-field transport, density of states (DOS), bandstructure, mobility and effective mass, in determining the eventual current drive needs

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[*] Corresponding author. Tel.*: + 1-650-7994083.*
*E-mail address:* tejask@stanford.edu

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a thorough and detailed investigation. Further, strain modifies the bandstructure [6] and dramatically changes the BTBT limited off-state leakage [9]. In this work, the bandstructures were calculated using the non-local Empirical Pseudopotential method [7]. Full-Band Monte-Carlo Simulations were used to evaluate the transport [8]. A 1-D Poisson-Schrodinger solver and detailed BTBT simulations (including direct and indirect transitions) were used to calculate the electrostatics and the off-state leakage. We systematically compare and benchmark nano-scale (Ts=5nm, Lg=15nm) DG p-FETs, with different high mobility channel materials Si and Ge, in terms of their important performance metrics - Drive Current, Intrinsic Delay and Off-state Leakage. Two standard channel directions, [100] and [110], on the (001) surface are considered.

## 2. Uniaxial strain

We have looked at uniaxially strained, Si and Ge MOSFETs on a (001) wafer with channel direction along [100] and [110]. Both tensile and compressive stresses from –5GPa to +5GPa were considered. In this simulation study we have extended our range of stress, however, it should be noted that values of stress >3GPa for bulk materials is very close to their fracture point and may be impractical to achieve. The uniaxial stress was applied along the channel direction. The channel direction is denoted ‘x’, the width direction ‘y’, and the direction perpendicular to the gate ‘z’.

## 3. Effective mass, DOS and bandgap

The effective masses are shown in Fig. 1. Along [100] Si, the effective mass reduces slightly for both tensile and compressive in all directions. Along Si [110], compressive stress rapidly decreases the mass in the transport direction (x) while greatly increasing the mass in the width direction (y), leading to a high density of states. For Ge, compressive stress allows a rapid decrease in transport mass and along the <110> direction it behaves similar to Si, allowing a simultaneous increase in the DOS.

The relative positions of all the different valleys for Ge [110] are shown in Fig. 2. The reduction in bandgap for compressive uniaxial stress along [100] for Si is always the X-valley. For Ge [110] it is the

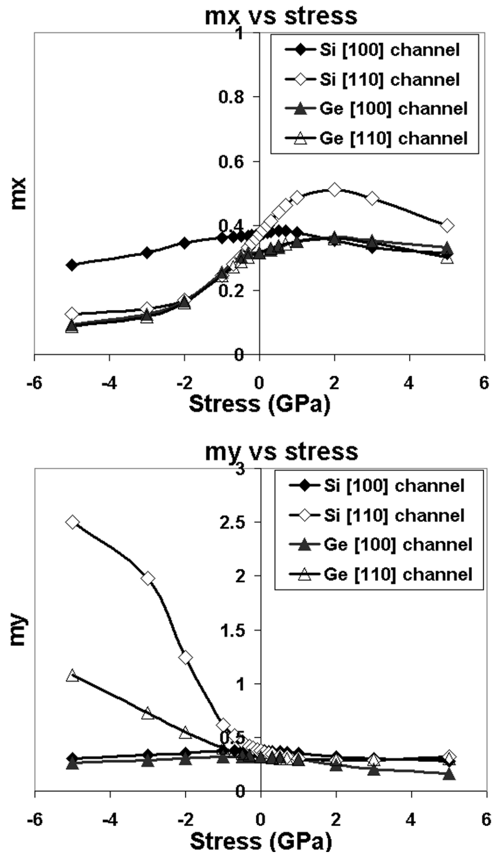

Fig. 1. (a) and (b): The effective mass for Si and Ge as a function of uniaxial strain. Si [110] and Ge [110] show a rapid reduction in mass along the channel and simultaneous increase in the width direction, with applied compressive stress.

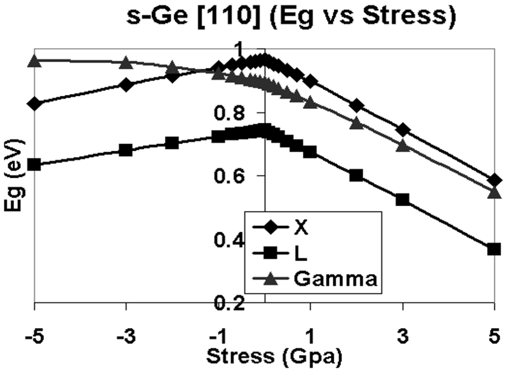

Fig. 2. The lowest valley for Ge [110] is always L- and the bandgap is relatively large even for large [110] uniaxial stress. The Γ- valley increases with compressive stress.

**(a)**

L-valley but for Ge [100], the lowest valley shifts from L- to X- for large values of stress, due to the rapid reduction in the X-valley bandgap. A seen in Fig. 2, for compressive stress in Ge [110], the Γ-valley bandgap increases, while for tensile it sharply reduces.

## 4. Low-field mobility and velocity-field curves

The effective, low driving field mobility in the channel transport direction for a 2-D hole inversion carrier concentration of $1.8\text{x}10^{13}\text{cm}^{-2}$ is shown in Fig. 3. The mobility for compressively strained [110] strained-Ge is the highest along the channel direction, due to its lower mass and lifting of the band degeneracy. The mobility is ~6X larger than for relaxed-Ge and ~2X larger than for [110] strained-Si. The mobility is enhanced by ~12X for strained-Ge [110], ~6X for strained-Si [110] and ~2X for relaxed-Ge, compared to relaxed-Si.

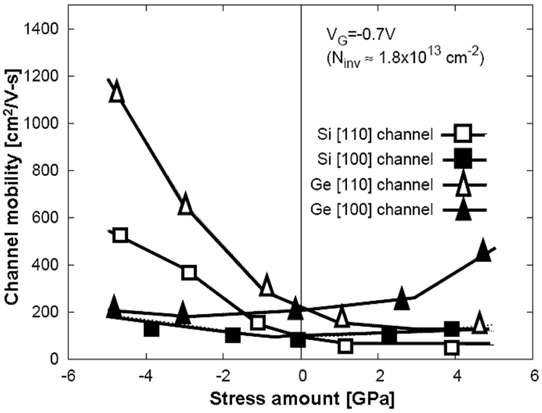

Fig. 3. The low-field mobility vs uniaxial stress for Si and Ge. Mobility is greatly enhanced along the channel for Ge [110] and Si [110] due to the low effective mass, reduced scattering and lifting of the band degeneracy.

The bulk velocity-field curves for Si and Ge under uniaxial strain are shown in Figs. 4 (a), (b) and (c) (relaxed, compressive and tensile stress). The bulk velocities for compressive Si [110], and Ge [110] are extremely large and exhibit stationary velocity overshoot under bulk conditions. Si [110] shows an enhancement of ~50%, and Ge [110] exhibits an enhancement of ~40%, compared to their relaxed unstrained cases respectively.

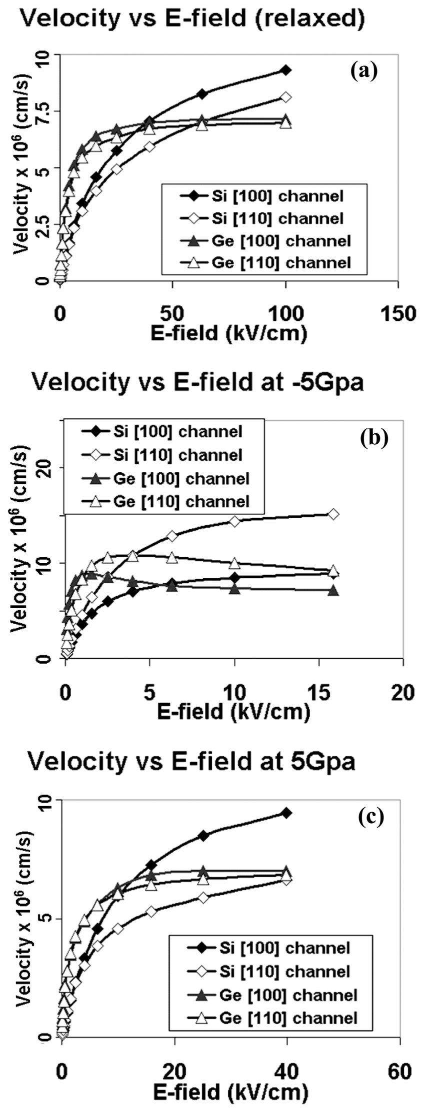

Fig. 4. (a), (b) and (c): The velocity-field curves for uniaxially strained Si and Ge compared to relaxed substrates. Si [110] shows a very large stationary velocity overshoot for uniaxial compressive stress under bulk conditions. The high field transport for Ge [110] is also greatly enhanced with uniaxial compressive stress.

## 5. Drive current, delay and off-state leakage

From Fig. 6, we find that the large enhancement in the bulk velocity at high driving fields, in compressive Si [110], leads to high drive currents. The higher mobility of compressively strained Ge [110] and the enhanced high driving field bulk velocity leads to a very high drive current, which is the highest among all the channels considered. The minimum off-state leakage in compressively strained Ge [110] is an order of magnitude lower than in strained Ge [100] because of the larger L- and Γ-valley band gaps (Fig. 5). Si [110] shows the lowest leakage, (100X lower than Ge), due to its large indirect X-valley band gap.

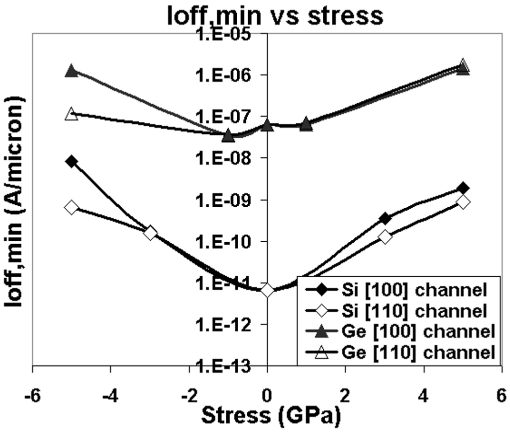

Fig. 5. The minimum achievable off-state leakage for [110] under compressive stress is lower than [100] for Si and Ge because of the larger bandgap. Si [110] shows the lowest leakage.

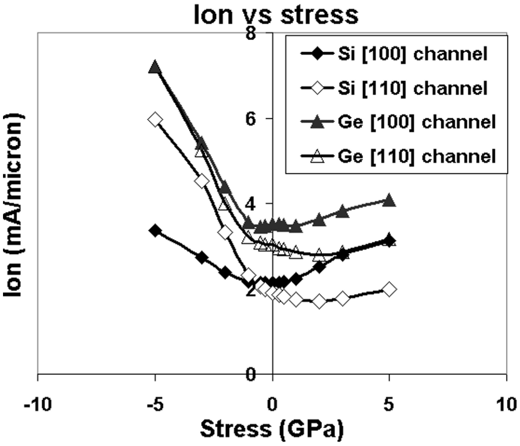

Fig. 6. The drive current for Ge [100] and Ge[110] under uniaxial compressive stress is greatly enhanced (3.5X). Si[110] also shows very high drive current (2.5X) due to enhanced high field transport and strongly anisotropic effective mass.

## 6. Conclusions

The role of strain, channel orientation, bandstructure, DOS, effective mass, bandgap, mobility and velocity in determining the performance is nanoscale pMOSFETs is examined. For lower values of uniaxial stress, compressively strained s-Ge gives the best performance in terms of drive current enhancement/delay reduction (~2X compared to r-Si). However, the minimum off-state leakage due to BTBT is rather high (100nA/µm). For larger values of uniaxial strain, mainly due to the large enhancement in the bulk velocity at high driving fields, the anisotropic effective mass and large band gap, Si [110] strained compressively to >-3GPa performs the best in terms of drive current enhancement / delay reduction (~3X) and very low off-state leakage (<1nA/µm). However, it should be noted that values of stress >3GPa for bulk materials is very close to their fracture point and may be impractical to achieve.

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