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Theoretical Investigation of Electrical Performance and Band Structure of P-MOSFETs with $Si_{1-x}Ge_x$ Source/Drain Stressors

Kah-Wee Ang[1], Yong-Tian Hou[2], Jagar Singh[2], Ming-Fu Li[2] and Yee-Chia Yeo[1]

[1]Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117576.
Phone: +65-6874-2298 Fax : +65-6779-1103 E-mail: yeo@ieee.org
[2]Institute of Microelectronics, 11 Science Park Road, Science Park-II, Singapore 117685.

1. Introduction

Strained channel transistors have been actively pursued for improving carrier mobility and transistor drive current. Biaxial tensile strained Si on relaxed $Si_{1-x}Ge_x$ buffer has been widely studied for improving both electron and hole mobilities, but the hole mobility enhancement diminishes at high effective vertical fields [1]. Recently, a novel p-channel transistor structure with $Si_{1-x}Ge_x$ source/drain (S/D) stressors has been demonstrated to enhance hole mobility even at high vertical fields [2]-[3]. In this paper, we examine the strain field in a transistor with $Si_{1-x}Ge_x$ source-drain stressors and quantitatively evaluate the strain-induced drive current enhancement by device simulation. In addition, the valence band structures for strained Si in the presence of a vertical field are investigated. This study points out the unique differences between biaxial tensile strained Si and uniaxial compressive strained Si at high effective vertical fields.

2. Results and Discussions

Finite Element Calculations on Strain Field

Fig. 1 shows a novel p-channel transistor structure featuring $Si_{1-x}Ge_x$ stressors in the source/drain region. Two-dimensional finite element calculations were performed to study the strain field in the vicinity of Si channel and the stressors [4]. A non-uniform finite element grid was adopted in which denser grids are defined at regions with larger strain gradient. The lattice-mismatch between the $Si_{1-x}Ge_x$ stressor and the Si channel was simulated in the framework of thermoelasticity [5], and the isotropic approximation was adopted.

The lattice mismatch between the $Si_{1-x}Ge_x$ stressor and the Si channel results in a strain field comprising of two major strain components: the lateral strain $\boldsymbol{e}_{xx}$ and the vertical strain $\boldsymbol{e}_{zz}$. For a transistor structure with inter-stressor spacing L of 50 nm, Ge content x of 0.25, and stressor depth d of 20 nm, the distribution of $\boldsymbol{e}_{xx}$ is depicted in Fig. 2, showing a large lateral compressive strain in the Si channel. The largest $\boldsymbol{e}_{xx}$ was observed at the Si surface where the inversion layer is formed, contributing favorably to carrier mobility enhancement. The $Si_{1-x}Ge_x$ stressor also stretches the Si lattice vertically with maximum vertical tensile strain $\boldsymbol{e}_{zz}$ near the vertical heterojunction (Fig. 3).

Impact of Strain on Transistor Performance

The impact of the strain components on linear drain current was evaluated in [6]. In this work, the strain field obtained from finite element calculation was translated into a spatially dependent mobility. The strain sensitivity of fractional change in mobility is taken to be -7.4×10^{-3} and 8.2×10^{-3} for $\boldsymbol{e}_{xx}$ and $\boldsymbol{e}_{zz}$, respectively [6]. The spatially dependent mobility was incorporated in a miniMOS-based device simulator to evaluate the transistor performance. The simulated linear drive current enhancement, $\Delta I_{DLIN}/I_{DLIN}$ is found to be approximately equal to the spatially averaged mobility enhancement. Figs. 4 and 5 denote the simulated electrical performance of a strained p-MOSFET. An astounding linear drive current I_{DLIN} enhancement of more than 60% was achieved for a transistor with L = 50 nm and x = 0.25 over a control unstrained device. Fig. 6 summarizes the effect of varying stressor spacing L and Ge content x on I_{DLIN} enhancement. Larger I_{DLIN} enhancement is possible with increasing Ge mole fraction in the stressor, assuming that mobility enhancement does not saturate at the strain levels considered. For a fixed Ge content, a smaller inter-stressor spacing enhances the beneficial strain and the transistor drive current further. This demonstrates the excellent scaling capability of the p-channel transistor with $Si_{1-x}Ge_x$ source/drain.

Strained Induced Band Structure Modification

The effect of strain on valence band structure is investigated next using k.p effective mass theory. Subband energies are calculated by solving the 6×6 Kohn Luttinger Hamiltonian with strain included [7].

The energy dispersions of the six lowest energy subbands in the inversion layer of PMOS transistors employing uniaxial compressive strained-Si (Fig. 7) and biaxial tensile strained-Si (Fig. 8) are investigated. HH, LH and SO denote the heavy, light and spin-orbit split-off hole bands, respectively. Strain lifts the degeneracy between HH and LH bands, suppresses interband phonon scattering, and contributes to performance enhancement. Strain also modifies the curvature near the subband energy maximum and affects the effective mass. The inter-subband energy splitting, Δ_{HH-LH} and normalized effective mass are plotted in Fig. 9 and 10, respectively, as a function of effective vertical field E_{eff} for both uniaxial compressive strained-Si and biaxial tensile strained-Si. For biaxial tensile strained-Si, the drastic increase in effective mass may account for the reduced mobility enhancement with increasing E_{eff} (Fig. 11). For the case of uniaxial compressive strained-Si, with increasing E_{eff}, the Δ_{HH-LH} splitting increases and the rise in effective mass is much gentler. This possibly explains the retention of the significant hole mobility enhancement even at large E_{eff} (Fig. 11). Table 1 summarizes the effect of increasing E_{eff} on the inter-subband energy splitting and effective hole mass for various strained-Si approaches. PMOS transistors with lateral compressive strain $\boldsymbol{e}_{xx}$ and vertical tensile strain $\boldsymbol{e}_{yy}$ is more favorable for mobility enhancement at high E_{eff}.

3. Conclusions

The strain field in a uniaxial strained p-channel transistor featuring $Si_{1-x}Ge_x$ source/drain stressors was simulated. Device simulations demonstrate increasing linear drive current enhancement with increasing Ge content or decreasing inter-stressor spacing. The difference in mobility enhancement behavior between uniaxial compressive strained-Si and biaxial tensile strained-Si is explained by an investigation of the valence band structures. Uniaxial strained-Si leads to a larger inter-subband energy separation and less degradation of effective mass.

References

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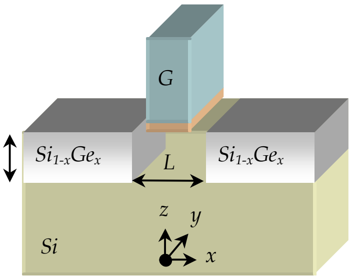

Fig. 1. Strained channel p-MOSFET with $Si_{1-x}Ge_x$ stressors in the source/drain regions.

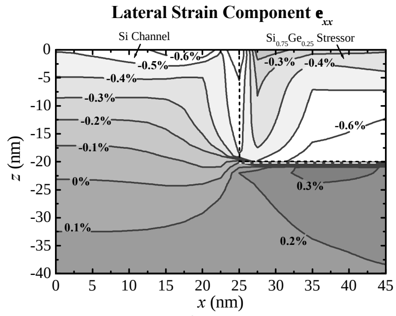

Fig. 2. Distribution of lateral strain component e_{xx} in right half of transistor, showing lateral compressive strain in Si channel. Inter-stressor spacing is 50 nm and Si-SiGe heterojunction is indicated by dashes.

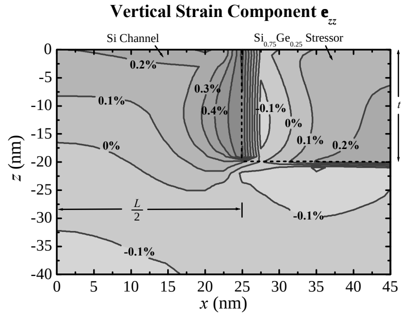

Fig. 3. Silicon lattice in channel region is vertically stretched while the SiGe lattice is vertically compressed near the vertical Si-SiGe heterojunction.

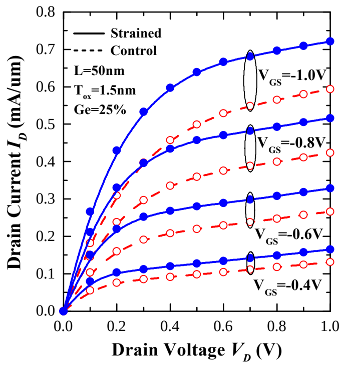

Fig. 4. I_D-V_D plot of strained channel PMOSFET with L_g=50nm, x=0.25, t_{ox}=1.5nm and d=20nm.

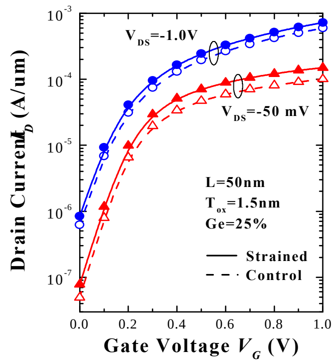

Fig. 5. I_D-V_G plot of strained channel PMOSFET. Linear drive current enhancement of more than 60% is achievable with L_g=50nm and x=0.25.

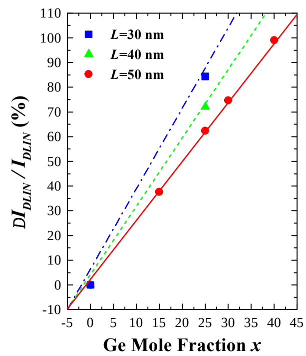

Fig. 6. Linear drain current enhancement $\Delta I_{DLIN}/I_{DLIN}$ improves with increasing Ge content x and decreasing inter-stressor spacing L.

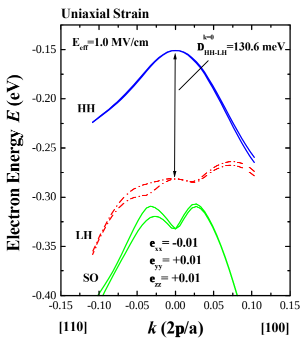

Fig. 7. Valence band dispersion of uniaxial strained Si, showing large interband energy separation and large curvature for the topmost energy subband.

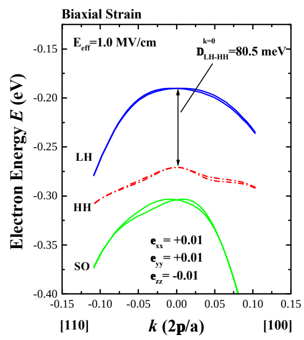

Fig. 8. Valence band dispersion of biaxial tensile strained Si at E_{eff} of 1 MV/cm, showing large effective mass in the topmost energy subband.

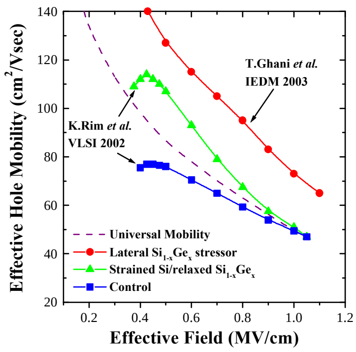

Fig. 11. Hole mobility as a function of effective vertical field for uniaxial strained [2] and biaxial strained [1] PMOSFET.

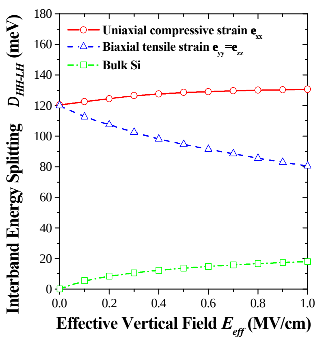

Fig. 9. Interband energy splitting at k = 0 as a function of effective vertical field E_{eff}. With increasing E_{eff}, the energy separation decreases for biaxial tensile strained Si but increases for uniaxial compressive strained Si.

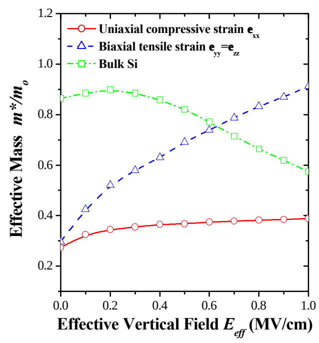

Fig. 10. Normalized effective mass in the [110] direction as a function of effective vertical field for strained channel and unstrained PMOSFETs. A large increase of effective mass at large E_{eff} is observed for biaxial tensile strained Si.

Table I. Summary of the effect of increasing effective vertical field on interband energy separation and effective mass for various strained-Si approaches.

	SiGe S/D Stressor		Si/SiGe
	e_{xx} = - # e_{yy} = + # e_{zz} = +	e_{xx} = - e_{yy} = 0 e_{zz} = +	e_{xx} = + e_{yy} = + e_{zz} = -
Energy Splitting Δ_{HH-LH}	- - - - *	- -	- -
Effective Mass m^*/m_o	— *	–	- - -

- denotes compressive and + denotes tensile.
* ↑ denotes increase while ↓ denotes decrease.