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Monte Carlo Simulation of Non-Local Transport Effects in Strained Si on Relaxed $Si_{1-x}Ge_x$ Heterostructures

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Electron transport properties of strained-Si on relaxed $Si_{1-x}Ge_x$ channel MOSFETs have been studied using a Monte Carlo simulator. The steady- and non-steady-state high-longitudinal field transport regimes have been described in detail. Electron-velocity-overshoot effects are studied in deep-submicron strained-Si MOSFETs, where they show an improvement over the performance of their normal silicon counterparts. The impact of the Si layer strain on the performance enhancement are described in depth in terms of microscopic magnitudes.

Keywords: Strained Si layer, electron velocity overshoot, conduction effective mass reduction, intervalley scattering rate reduction, Monte Carlo simulation

1. INTRODUCTION

Recently, both theoretical and experimental works have shown important electron mobility enhancement when silicon is grown pseudomorphically on relaxed $Si_{1-x}Ge_x$ at different temperatures. The strain causes the six-fold degenerate valleys of the silicon conduction band minimum to split into two groups: two lowered valleys with the longitudinal effective mass axis perpendicular to the interface, and four raised valleys with the longitudinal mass axis parallel to the interface. This splitting reduces the intervalley phonon scattering rate compared with that of unstrained silicon. In addition, in the lowered valleys, which are more populated in the strained case, electrons show a smaller conduction effective mass (transverse mass) in transport parallel to the interface. The combination of the light effective mass and reduced intervalley scattering gives rise to higher electron mobility [1]. Moreover, the lower intervalley-scattering rates make the energy relaxation times higher, originating important electron velocity overshoot. These advantages can be used to improve MOSFETs parameters, taking advantage both of the higher carrier mobility and the higher electron velocity overshoot, thus greatly improving short channel MOSFET transconductance.

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2. MONTE CARLO SIMULATOR

We have developed a strained-Si-*n*-type Monte Carlo simulator by adapting a previous unstrained-Si one which includes inversion-layer quantization and a nonparabolic band model [2]. The quantization effects are included by solving the Poisson equation coupled with the one-dimensional Schrodinger equation all along the channel. The value of the conduction band offset for the four-fold in-plane bands over the value for the two-fold out-of-plane bands was $0.67x$ eV, where x was the Ge mole fraction [3] and the valley shape was not modified by the strain. The two-dimensional Poisson equation is solved throughout the MOSFET to account for short-channel effects. Phonon, surface-roughness and Coulomb scattering rates have been evaluated at each point of the channel [3]. The electron energy for all our simulations was always under 0.5 eV, and so a nonparabolic simplified band structure can be used to accurately describe the Si band structure [4].

3. RESULTS

We have simulated strained-Si on relaxed $Si_{1-x}Ge_x$ long-channel MOSFETs in order to obtain the steady-state electron velocity and energy curves versus the longitudinal-electric field (see Fig. 1). After having fixed the transverse-electric field we increased the longitudinal field step by step, recording the most important transport magnitudes when the steady-state was reached. The saturation velocities obtained were almost the same for all Ge mole fractions: 1.1×10^7 cm/s at 300 K and 1.4×10^7 cm/s at 77 K, although they were a bit higher ($\approx 1-2\%$) for $x > 0$.

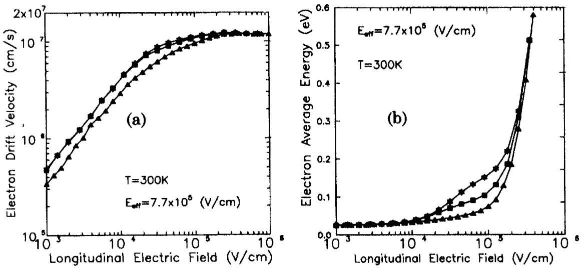

FIGURE 1 Steady-state drift-electron-velocity curves (a) and electron-average energy (b) versus longitudinal-electric field for $E_{\mathrm{eff}}=7.7\times10^5$ V/cm at $T=300$ K. (▲: $x=0$; ■: $x=0.2$; $*$: $x=0.4$). The high effective field chosen is typical of very short channel MOSFETs where high doping profiles and thin oxides are used.

The energy- and momentum-relaxation times can be calculated making use of the data shown in Figure 1. Different relaxation times are obtained as x changes. The momentum- and energy-relaxation times, for different Ge mole fractions and temperatures are shown in Figure 2. The momentum-relaxation times are smaller than the energy ones. The difference between the momentum- and energy-relaxation times produces nonlocal electron transport effects such as electron-velocity overshoot [5]. These effects are expected to occur on a time scale shorter than the energy-relaxation time. It is foreseeable that the higher energy-relaxation times observed in Figure 2 as x rises lead to increased electron velocity-overshoot effects and therefore higher MOSFET transconductances as channel dimensions are reduced. The relaxation times are lower at low temperature than at room temperature and therefore electron velocity overshoot effects are higher at low temperature as it shown in Figure 3.

We have studied velocity-overshoot effects by applying a sudden longitudinal-electric field of 2×10^5 V/cm to a steady-state electron distribution achieved under the influence of a longitudinal-electric field of 1×10^4 V/cm. The time evolution of

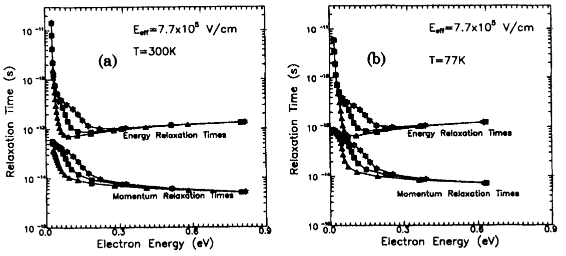

FIGURE 2 Energy- and momentum-relaxation times versus electron energy for $E_{\mathrm{eff}} = 7.7\times10^5$ V/cm at $T=300$ K (a) and $T=77$ K (b). (▲: $x=0$; ■: $x=0.2$; $*$:$x=0.4$).

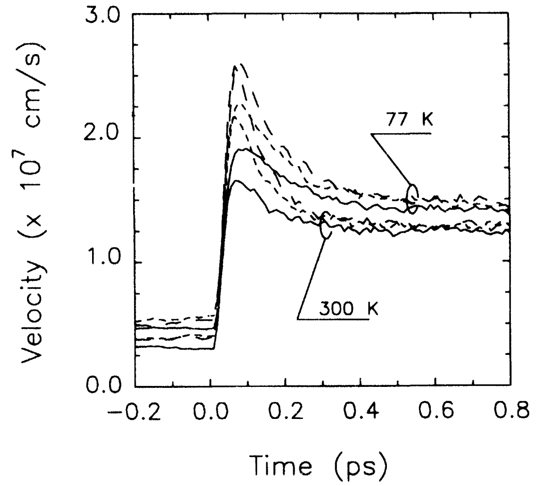

FIGURE 3 Transient overshoot velocity with a sudden application of the field 2×10^5 V/cm at room and low temperature for $E_{\text{eff}} = 7.7\times10^5$ V/cm. Unstrained-silicon (solid line), $x = 0.2$ (short dashed line), $x = 0.4$ (long dashed line).

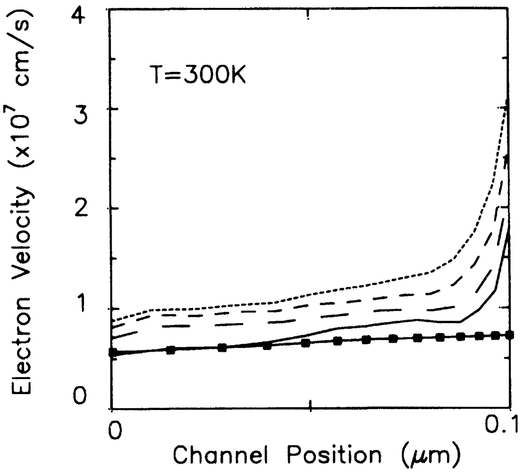

FIGURE 4 Electron velocity versus channel position at $T = 300$ K. Velocity distribution obtained in an 0.1 μm MOSFET with $V_{\text{GS}} = 1.3$ V and $V_{\text{DS}} = 0.5$ V for $x = 0$ (solid line), $x = 0.1$ (long dashed line), $x = 0.2$ (medium dashed line), $x = 0.3$ (short dashed line). Low longitudinal-electric-field velocity corrected using Thornber's expression and the longitudinal field distribution obtained for the previous MOSFET with $x = 0$ (Squares).

the electron velocity is shown in Figure 3. It is clear that the time taken to reach the steady-state velocity corresponding to a longitudinal-electric field of 2×10^5 V/cm increases as x rises. This result is coherent with the energy-relaxation times shown in Figure 2. It is clear that the increase of the energy-relaxation times as x rises causes the time taken to reach the steady-state to be longer and hence enhances the velocity-overshoot effects.

We have simulated several 0.1 μm channel length MOSFETs for $x = 0, 0.1, 0.2$ and 0.3 (the thickness of the strained Si layer is 4.6 nm). The MOSFET external bias was $V_{\text{DS}} = 0.5$ V, $V_{\text{GS}} = 1.5$ V, and $V_{\text{SB}} = 0$. The velocity distribution along the channel obtained for each Ge mole fraction is plotted in Figure 4 at room temperature. The electron velocity is higher than the saturation velocity for strained and unstrained-Si channel MOSFETs near the drain edge. This effect is due to the high longitudinal electric-field gradient the carriers face as they travel toward the drain. This gradient makes the electrons overshoot the velocity they would have if they were subject to steady-state transport.

4. CONCLUSIONS

A Monte Carlo simulator has been used to study the electron transport properties of strained-Si on relaxed $Si_{1-x}Ge_x$ channel MOSFETs and the performance improvement of these devices at high-longitudinal fields. Similar saturation velocities are obtained no matter the value of the Ge mole fraction, however the electron velocity overshoot effects increase as the Ge mole fraction rises.

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Authors' Biographies

Francisco Gámiz graduated with a degree in physics in 1991, and received the Ph.D. in 1994 from the University of Granada. Since 1991 he has been working on the characterization of scattering mechanisms and their influence on the transport properties of charge carriers in semiconductor heterostructures. His current research interest includes the effects of many-carriers on the electron mobility and the interpretation of the influence of high longitudinal electric fields have on MOS transistors. Current interest are also related to SiGe and SiC, and SOI devices, and quantum transport. He has coauthored several papers in all these subjects. He is an Associate Professor at the University of Granada.

Juan B. Roldán graduated with a degree in physics in 1993, and received the Ph.D. in 1997 from the University of Granada. Since 1993 he has been working on the MOS device including 2D transport, non-local effects and Monte Carlo simulations. Current interests are also related to SiGe and SiC devices. He is a Teaching Assistant at the University of Granada.

Juan A. López-Villanueva graduated in 1984, Ph.D. in 1990 (University of Granada) with a thesis on the degradation of MOS structures by Fowler-Nordheim tunneling. Since 1985 he has been working on deep-level characterization and, mainly, MOS device physics, including Fowler-Nordheim and direct tunneling, quantum effects, 2D transport, effects of nonparabolicity, scattering mechanisms and Monte Carlo simulation of charge transport. He has coauthored several papers in all these subjects. His current research interest includes, simulation and modelling of electron devices. His educational activities also include analog systems for electronic instrumentation and power electronics. He is an Associated Professor at the University of Granada.