Enhanced Hole Mobility in High Ge Content Asymmetrically Strained-SiGe p-MOSFETs

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Leonardo Gomez, C. Ni Chléirigh, P. Hashemi, and J. L. Hoyt

***Abstract*—The hole mobility characteristics of ⟨110⟩/(100)-oriented asymmetrically strained-SiGe p-MOSFETs are studied. Uniaxial mechanical strain is applied to biaxial compressive strained devices and the relative change in effective hole mobility is measured. The channel Ge content varies from 0 to 100%. Up to −2.6% biaxial compressive strain is present in the channel and an additive uniaxial strain component of −0.06% is applied via mechanical bending. The hole mobility in biaxial compressive strained-SiGe is enhanced relative to relaxed Si. It is observed that this mobility enhancement increases further with the application of ⟨110⟩ longitudinal uniaxial compressive strain. The relative change in mobility with applied stress is larger for biaxial compressive strained-SiGe than for Si and increases with the amount of biaxial compressive strain present in the channel.**

***Index Terms*—Hole mobility, piezo coefficients, p-MOSFET, Silicon Germanium, strain.**

I. Introduction

NOVEL CMOS channel materials and device architectures are of interest for enhancing carrier transport metrics and increasing device performance [1]–[6]. In biaxial compressive strained-SiGe, exceptionally high hole mobility gains have been observed relative to relaxed-Si. Over a 10x hole mobility enhancement relative to relaxed-Si has been measured for biaxial compressive strained-Ge channel p-MOSFETs pseudomorphic to relaxed-$Si_{0.5}Ge_{0.5}$ [2]. The hole mobility improvement observed in biaxial compressive strained-SiGe stems from a reduction in the carrier's conductivity effective mass and a reduction in phonon scattering [7]–[9]. To date though, there are no experimental reports examining the transport impact of combining biaxial and additive uniaxial compressive strain in high-Ge content strained-SiGe channel devices. Existing work is limited to low-Ge content devices with small amounts of in-plane biaxial compressive strain [10]. In this letter, the hole mobility characteristics of high-Ge content biaxial compressive strained-SiGe p-MOSFETs with additive uniaxial strain are examined.

II. Experiment

Uniaxial longitudinal compressive strain was applied mechanically to ⟨110⟩/(100)-oriented biaxial compressive strained SiGe p-MOSFETs. The channel structure consists of a Si cap (∼2 to 3 nm) and a buried strained-SiGe channel (∼5 to 7 nm). The channel was phosphorus doped with a nominal concentration of 1×10^{17} cm^{-3}. The channel doping was consistent across all devices, making the vertical field profiles similar. The gate oxide thickness was 3.5 nm in all a cases, except for the Ge-channel device where it is 11 nm. The maximum thermal budget was the source drain activation anneal, which was 10 seconds at 800 °C for strained-Ge channel compositions up to 70% and 10 seconds at 650 °C for strained-Ge channels. Details of the device fabrication are described in [11] for devices on Si substrates and in [12] for those on SiGe virtual substrates. The biaxial compressive strain present in the strained-$Si_{1-x}Ge_x$ channel varies depending on the Ge composition of the relaxed-$Si_{1-y}Ge_y$ substrate, where $0 < x < 1$ and $0 < y < 0.4$ in this study. Table I summarizes the device structures examined in this work and indicates the calculated levels of the biaxial compressive strain present in the channel. The X/Y notation is utilized to indicate the channel (X) and the virtual substrate (Y) Ge compositions, respectively. The channel Ge composition was determined by either Secondary Ion Mass Spectroscopy (SIMS) or Rutherford Back Scattering (RBS) after device processing. The measured channel Ge compositions are comparable to the targeted values, i.e., 40%, 60%, and 100%, suggesting minimal strain relaxation via interdiffusion. The channel strain reported in Table I was calculated from the relation $\varepsilon = 1 - a_x/a_y$, where a_x and a_y are the $Si_{1-x}Ge_x$ and $Si_{1-y}Ge_y$ lattice constants in the channel and virtual substrate, respectively. Additive ⟨110⟩ uniaxial strain was applied using a mechanical bending apparatus. The level of applied mechanical strain was measured using a commercial strain gauge adhered to the wafer backside. Gauge measurements indicate that up to −0.06% strain was applied using the bending apparatus.

TABLE I
Channel and Substrate Ge Percentage as Well as the Calculated of Biaxial Compressive Strain Present in the Channel. Calculations Were Based on Measured Values of the Channel Ge Percentage

Device Structure	Channel Ge%	Substrate Ge%	Biaxial Compressive Strain
100/40	100 %	40 %	-2.4 %
63/0	63 %	0 %	-2.6 %
58/30	58 %	30 %	-1.1 %
43/0	43 %	0 %	-1.8 %
42/30	42 %	30 %	-0.5 %
Si control	0 %	0 %	0 %

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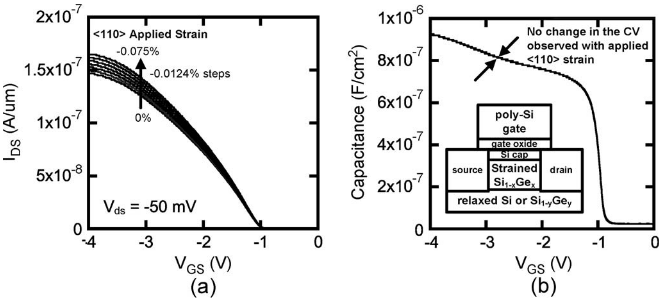

Fig. 1. (a) Transfer characteristics for a 43/0 p-MOSFET with applied ⟨110⟩ longitudinal uniaxial strained. The arrows indicate the direction of increasing uniaxial compressive strain starting from 0% strain at the lowest curve and increasing in 0.0124% increments. (b) The C–V characteristics with applied strain for the same 43/0 p-MOSFET in (a). The seven C–V curves overlay, which indicates no change in inversion charge density or distribution with applied ⟨110⟩ uniaxial compressive strain. The inset shows the channel layers of the p-MOSFETs in this work, including the gate stack, Si cap, strained-SiGe channel, and underlying substrate.

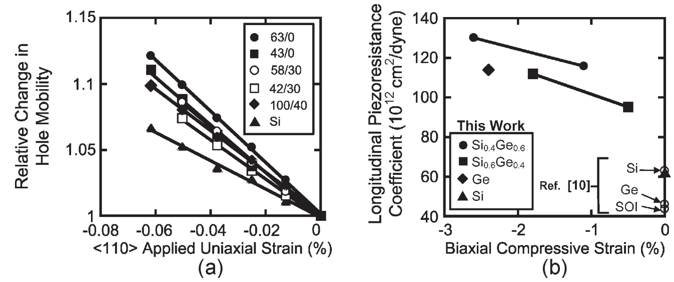

Fig. 3. (a) The relative mobility enhancement for the devices in Table I with applied ⟨110⟩ uniaxial compressive strain. Si, 43/0, 63/0, and 100/40 MOSFETs are represented by the closed symbols while the open symbols represent the results for 58/30 and 42/30 MOSFETs. (b) Longitudinal piezoresistance coefficients plotted as a function of biaxial compressive strain. The coefficients for the Si strained-Ge (i.e., 100/40), strained-$Si_{0.6}Ge_{0.4}$ (i.e., 43/0 and 42/30), and strained-$Si_{0.4}Ge_{0.6}$ (i.e., 63/0 and 58/30) channel devices described in Table I are provided. Piezoresistance coefficients for relaxed bulk Si, Ge, and SOI reported by Weber in [14] are also plotted (open symbols).

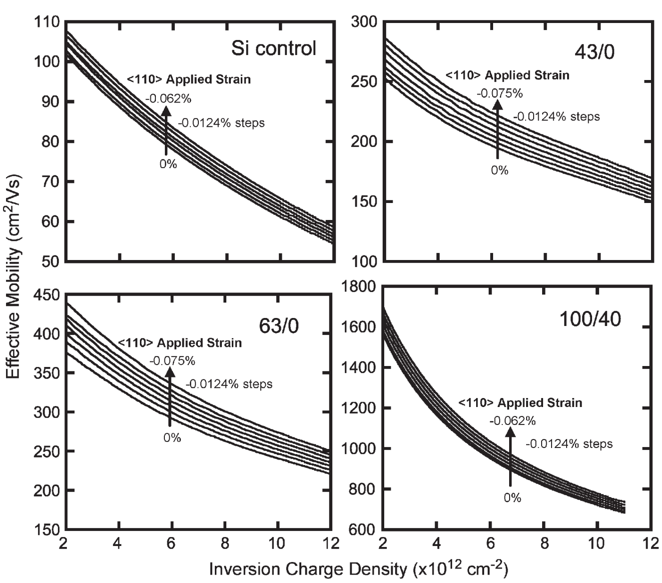

Fig. 2. Effective hole mobility curves for Si, 43/0, 63/0, and 100/40 MOSFETs for various values of applied ⟨110⟩ longitudinal uniaxial compressive strain. The arrows indicate the direction of increasing uniaxial compressive strain starting from 0% strain at the lowest curve and increasing in 0.0124% increments.

A mobility extraction MOSFET structure was utilized to extract the effective mobility independent of the extrinsic parasitic resistance [13]. The device gate length is 100 μm and the width is 15 μm. The effective hole mobility was extracted using the transfer (I_{DS}–V_{GS}) and capacitance-voltage (C–V) characteristics measured on each device as uniaxial strain was applied (Fig. 1). An increase in on-current is observed with increasing longitudinal uniaxial compressive strain. No change in the threshold voltage or $\mathrm{C}_{\max}$ was observed with applied strain. This indicates that the observed change in current stems from a change in the effective hole mobility and that the carrier confinement in the strained $\mathrm{Si}_{1-x}\mathrm{Ge}_x$ channel does not change with applied strain. The hole mobility curves for some of the devices in Table I are plotted in Fig. 2. The arrows indicate the direction of increasing applied mechanical strain. The relative mobility enhancements are also plotted in Fig. 3(a) for an inversion charge density $\mathrm{N}_{\mathrm{inv}} = 4 \times 10^{12}\ \mathrm{cm}^{-2}$. The carrier density at which the mobility enhancement comparison is made corresponds to an approximate gate-to-source voltage of -1.9 V in Fig. 1. This bias point is in the plateau region of the C–V characteristics, where carriers predominantly occupy the buried SiGe channel [4], [11], [15].

III. Discussion

It is interesting to see that the substantial hole mobility enhancement provided by biaxial compressive strained-SiGe relative to relaxed Si continues to increase with the application of ⟨110⟩ uniaxial compressive strain. Also worth noting is that the relative change in mobility for biaxial compressive strained-SiGe devices is larger than that of Si. Fig. 3(a) shows that the hole mobility in biaxial compressive strained-SiGe (e.g., 43/0, 63/0, and 100/40) expresses a greater sensitivity to applied uniaxial strain than Si. Data for p-MOSFETs with fixed nominal channel Ge concentration and varied virtual substrate composition is also plotted in Fig. 3(a) and shows that the sensitivity to applied uniaxial mechanical strain increases as the amount of biaxial compressive strain in the channel is increased. The longitudinal piezoresistance coefficients (π_L) are plotted as a function of the biaxial strain in Fig. 3(b) to better examine this effect. The piezoresistance coefficients for relaxed Si, Ge, and SOI reported by Weber in [10] are also plotted for comparison. The longitudinal piezoresistance coefficients were extracted in accordance with $\mu/\mu_o = -(\pi_L\sigma_L + \pi_T\sigma_T)$, also from [10]. The piezoresistance coefficients in Fig. 3(b) are grouped according to the nominal channel Ge composition (i.e., Si, $\mathrm{Si}_{0.6}\mathrm{Ge}_{0.4}$, $\mathrm{Si}_{0.4}\mathrm{Ge}_{0.6}$, and Ge). The piezoresistance coefficients appear to be correlated to the initial biaxial compressive strain in the channel. As the channel biaxial strain increases, a substantial rise in π_L is observed. This effect though does not appear to be directly correlated to the channel Ge fraction. The piezoresistance coefficients rise as the nominal channel Ge composition increases from 40% to 60%, but then decrease when the channel Ge composition reaches 100%.

In relaxed Si and Ge, small amounts of applied uniaxial strain (i.e., less than 500 MPa) provide an increase in mobility that is driven by a reduction in the carrier effective mass more so than a modulation in the scattering characteristics [9], [14]. The hole mobility in biaxial compressive strained SiGe exhibits a greater sensitivity to applied mechanical strain than relaxed Si or Ge. This suggests that either a larger reduction in the hole effective mass is occurring in initially biaxially strained material or that the hole mobility is also benefiting from a reduction in scattering (e.g., alloy scattering). Further investigation is required to determine the origin of this behavior.

IV. Summary

In this letter, we measured the hole mobility response of high-Ge-content biaxial compressive strained-SiGe p-MOSFETs to mechanically applied $\langle 110 \rangle$ uniaxial compressive strain. The hole mobility in biaxial compressive strained-SiGe p-MOSFETs continues to increase with applied uniaxial compressive strain and exhibits a larger relative change in mobility than Si. The longitudinal piezoresistance coefficients for biaxial compressive strained-SiGe are observed to be larger than in relaxed Si or Ge and are observed to increase with increasing biaxial compressive strain present in the channel.

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