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Experimental Study of Uniaxial Stress Effects on Coulomb-limited Electron and Hole Mobility in Si-MOSFETs

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Introduction

Performance enhancement of FETs by well-controlled stress is already a standard technique in aggressively scaled LSI technology [1-4]. Particularly, uniaxial stress is important from an industrial point of view, since this technique is already widely used in mass production. Therefore, mechanisms of electron and hole mobility (μ_e and μ_h) enhancements by uniaxial stress have been studied by many authors [1,5-8]. However, these studies have been performed on FETs with low substrate doping concentration (N_{sub}). Thus, stress effects on Coulomb scattering have not been understood nor investigated yet [9-11], in spite of the fact that extremely high-N_{sub} channels are required in future short-channel FETs. In this study, uniaxial stress effects on n- and p-FETs with various N_{sub} are systematically investigated for the first time, and stress dependence of Coulomb-limited mobility (μ_{Coulomb}) is extracted. As a result, the enhancement of μ_{Coulomb} by uniaxial stress in p-FETs is demonstrated for the first time.

Experimental Setup

We used long-channel (50-100 μm) n- and p-FETs with various N_{sub} fabricated on Si (001). Channel directions were aligned to <110> direction. The split C-V technique was adopted to characterize inversion carrier density (N_{inv}) and depleted impurity concentration in FETs. Four point bending was employed to apply uniaxial stress along the channel direction in order to rigidly study stress effects, with eliminating other differences between devices with and without stress [5,7].

Results and Discussion

A. Stress Effects on Coulomb Scattering in n-FETs

Figs. 1 and 2 show μ_e and μ_h in various N_{sub} FETs as a function of effective fields (E_{eff}), respectively. Effects of tensile and compressive stress are also shown. In Figs. 1 and 2, μ_e and μ_h are modulated by stress, regardless of N_{sub}. Tensile stress improves μ_e and degrades μ_h, whereas compressive stress improves μ_h and degrades μ_e.

Fig. 3 shows μ_e enhancement ratio, $\Delta\mu_e/\mu_e$, in two different N_{sub} n-FETs as a function of E_{eff}. Note that $\Delta\mu_e/\mu_e$ in the higher N_{sub} FET is sharply dropped when E_{eff} is lower than 0.2 MV/cm, while $\Delta\mu_e/\mu_e$ in the lower N_{sub} device is kept in higher values. In such a low E_{eff}, Coulomb scattering is the major scattering factor in the higher N_{sub} FET, while phonon scattering is still dominant in the lower N_{sub} FET. Hence, the reduction of $\Delta\mu_e/\mu_e$ in the higher N_{sub} FET indicates that Coulomb scattering is less suppressed by stress than phonon scattering. To examine stress effects on μ_{Coulomb} more directly, we extracted μ_{Coulomb} by using Matthiessen's rule. Fig. 4 shows μ_{Coulomb} in n-FETs with and without stress as a function of N_{inv}, demonstrating that μ_{Coulomb} is not modulated by stress. This result is reasonable, based on the reported physical origin of stress effects on μ_e [1,5,12]; with modest stress in the present experiments, the repopulation of electrons between subbands is negligible. Therefore, μ_{Coulomb} is not changed by stress in n-FETs.

B. Stress Effects on Coulomb Scattering in p-FETs

Fig. 5 shows μ_h change by stress, $\Delta\mu_h/\mu_h$, in two different N_{sub} p-FETs as a function of E_{eff}. Contrary to n-FETs, $\Delta\mu_h/\mu_h$, of the higher N_{sub} FET in the E_{eff} where Coulomb scattering mainly limits μ_h, is almost the same as that of the lower N_{sub} FET, indicating μ_{Coulomb} is enhanced by uniaxial stress by the same amount of magnitude as phonon-limited mobility (μ_{phonon}) is. Fig. 6 shows extracted μ_{Coulomb} in p-FETs with and without stress as a function of N_{inv}. μ_{Coulomb} is explicitly modulated by uniaxial stress. Fig. 7 compares enhancement ratio of μ_{Coulomb} and μ_{phonon} with various stress amounts. It is obvious that the enhancement ratio of μ_{Coulomb} by stress is the same as that of μ_{phonon}. It should be noted that reduction of intersubband scattering has impacts only on μ_{phonon}, while the change of net hole effective mass along the conductivity direction (m_{hc}*) influences both μ_{Coulomb} and μ_{phonon}. Therefore, the great enhancement of μ_{Coulomb} in p-FETs is reasonable if the mobility enhancement is caused by decrease of net m_{hc}* [1,6], but not by reduction of intersubband scattering induced by subband splitting.

To support the net m_{hc}* change model, we calculated valence band structures of bulk Si with and without stress using empirical pseudopotential method. In calculations, uniaxial stress corresponds to 0.1% strain was applied along the channel direction. Figs. 8(a) and (b) show calculated valence band structures without and with stress, respectively. In Fig. 8(b), the subband splitting by stress at Γ point is only 3.6 meV, which is much smaller than thermal energy at room temperature and optical phonon energy. Thus, effects of subband splitting on μ_h enhancement are negligible. On the other hand, m_{hc}* is greatly reduced by stress, particularly due to the effective mass decrease in the lowest subband. These calculations verify that μ_{Coulomb} enhancement in p-FETs by uniaxial stress experimentally observed in this study is induced by reduction of net m_{hc}*.

Conclusions

For better stress engineering in short channel FETs, uniaxial stress effects on μ_{Coulomb} in n- and p-FETs were investigated. Through careful studies, it was demonstrated for the first time that uniaxial stress enhances $\mu_{Coulomb}$ in p-FETs, whereas not in n-FETs. $\mu_{Coulomb}$ enhancement in p-FETs by stress was attributed to net m_{hc}* reduction, and validity of this was confirmed by calculations. On the contrary, no enhancement of $\mu_{Coulomb}$ in n-FETs was ascribed to negligibly small electron repopulation between subbands with the modest stress in this study.

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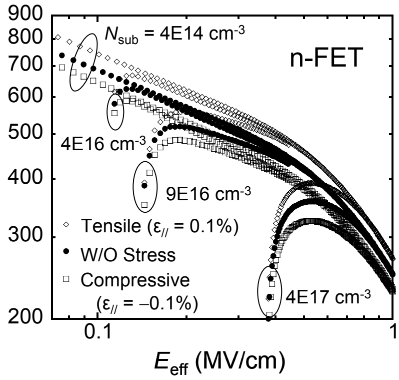

Fig. 1. Electron mobility (μ_e) versus effective field characteristics in n-FETs with various channel doping (N_{sub}) under uniaxial stress along the channel direction. μ_e is enhanced by tensile stress, and is decreased by compressive stress.

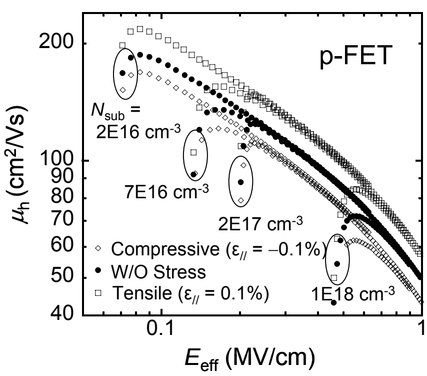

Fig. 2. Hole mobility (μ_h) versus effective field characteristics in p-FETs with various channel doping (N_{sub}) under uniaxial stress along the channel direction. μ_h is enhanced by compressive stress, and is decreased by tensile stress.

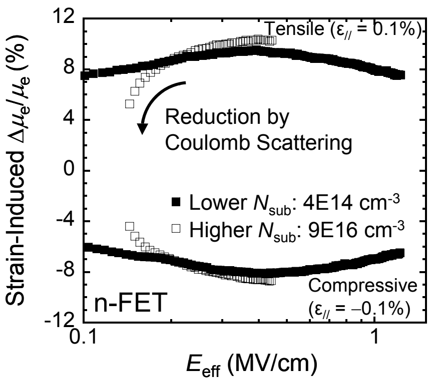

Fig. 3. Change of electron mobility, $\Delta\mu_e/\mu_e$, due to uniaxial stress. $\Delta\mu_e/\mu_e$ in the higher-N_{sub} device is distinctively dropped in a lower effective field region, where the total mobility is limited by Coulomb scattering.

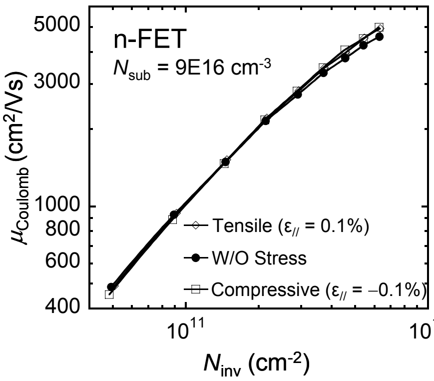

Fig. 4. Coulomb-limited mobility ($\mu_{Coulomb}$) versus inversion carrier density (N_{inv}) characteristics in n-FETs under various stress conditions. $\mu_{Coulomb}$ is extracted by using Matthiessen's rule. No modulation of $\mu_{Coulomb}$ is observed.

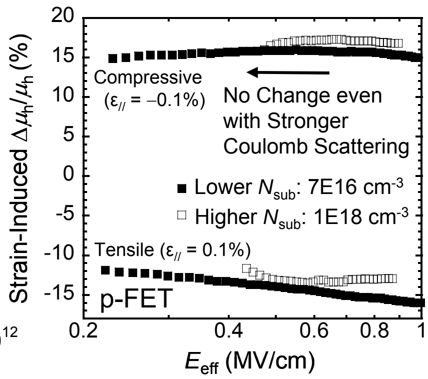

Fig. 5. Change of hole mobility, $\Delta\mu_h/\mu_h$, by uniaxial stress. $\Delta\mu_h/\mu_h$ in the higher-N_{sub} FET is the same as that in the lower-N_{sub} FET over a wide range of effective fields; no reduction of $\Delta\mu_h/\mu_h$ is observed in the higher-N_{sub} FET, which suggests stress-induced modulations of $\mu_{Coulomb}$.

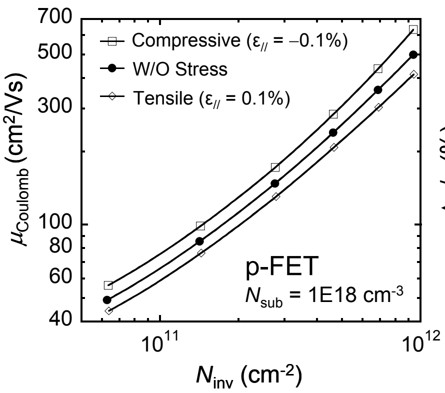

Fig. 6. $\mu_{Coulomb}$ versus N_{inv} characteristics in p-FETs under various stress conditions. It is clearly demonstrated that $\mu_{Coulomb}$ is improved by compressive stress, whereas it is degraded by tensile stress.

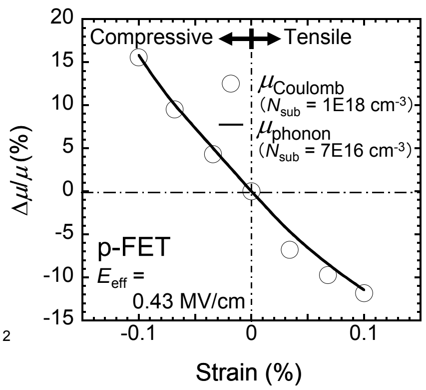

Fig. 7. Stress-induced change of Coulomb-limited hole mobility, $\Delta\mu_{Coulomb}/\mu_{Coulomb}$, as a function of strain. It is obvious that $\Delta\mu_{Coulomb}/\mu_{Coulomb}$ is enhanced by greater amount of stress in the identical way to the improvement ratio of phonon-limited hole mobility denoted a curve in Fig. 7.

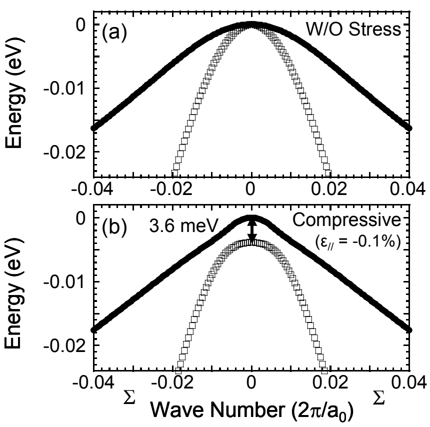

Fig. 8. Calculated valence band structures without (a) and with compressive stress (b). The subband splitting by uniaxial stress is as small as 3.6 meV, whereas conductivity effective mass of holes in the lowest subband is greatly reduced.