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A COMPREHENSIVE STUDY OF COULOMB SCATTERING MOBILITY IN SHORT-CHANNEL PROCESS-INDUCED STRAIN NMOSFETS

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ABSTRACT

This paper provides a comprehensive investigation of stress effects on Coulomb mobility in short channel strained nMOSFETs. Firstly, we examine the Coulomb mobility dependency on stress under various temperatures. It shows strong temperature dependency because interface scattering counteracts the stress sensitivity of the bulk charge limited mobility. Secondly, the electron screening effect on bulk charge also shows stress dependence because inversion charge density is engineered by strain-induced subband splitting and electron repopulations.

INTRODUCTION

Uniaxial strained-Si technology is crucial to transistor performance in nanoscale CMOS development [1]. The improvement of drive current shows strong correlation with the low-field mobility enhancement by uniaxial strain [2]. Recently, several studies [3-7] reported degraded carrier mobility for short channel devices and pointed out the increasing importance of Coulomb scattering. Whether or not Coulomb scattering mobility can be enhanced by process-induced strain merits investigation.

Although previous studies [4-5,8] have shown that Coulomb mobility is not enhanced in strained-Si nMOSFETs, Weber and Takagi [3] have demonstrated that the mobility limited by substrate impurity scattering is still enhanced in long-channel strained devices (L=10μm). These findings seem to be inconsistent, and further examination of Coulomb mobility is needed.

In this work, we tackle the problem using advanced short-channel strained devices. By accurate mobility extraction using various temperatures, we assess the impact of process-induced uniaxial strain on Coulomb mobility in short-channel nMOSFETs.

EXPERIMENTAL

N-channel devices with neutral and compressive stressors are manufactured by state-of-the-art CMOS processes, as shown in Fig. 1. Effective gate length ranges from 970nm to 90nm. Electrical measurements were implemented at 3 different temperatures: 85°C, 25°C, -40°C, respectively.

RESULTS AND DISCUSSION

Table I shows the summary table of stress dependence of Coulomb mobility limited by different mechanisms and scattering sources with compressive stress applied along <110> channel direction: (a) N_a scattering limited $\mu_{Coulomb}$ shows degradation due to heavier effective mass (m*) [3] (b) N_{it} scattering limited $\mu_{Coulomb}$ shows enhancement due to thicker inversion layer thickness (Z_{inv}) [3] (c) N_a screening limited $\mu_{Coulomb}$ shows degradation due to lower electron density (This work) (d) N_{it} screening limited $\mu_{Coulomb}$ shows no stress sensitivity on $\mu_{Coulomb}$ due to the Quantization effect caused by high Na [5]. Fig.2 shows the Ion-Ioff characteristic with neutral and compressive stressors and it shows significant difference. In order to extract short channel mobility, the intrinsic drain current was calibrated by considering the series-resistance (R_{sd}) effect [10]. μ, Q_{inv}, E_{EFF} and L_{EFF} can be obtained by split CV method [11].

Fig.3 shows the extracted mobility by considering asymmetry spatial distribution of Q_{inv} due to V_D bias [12]. Because V_D is 5mV only, the impact on mobility caused by the asymmetry spatial distribution at low Q_{inv} region is negligible. Fig. 4 shows the extracted mobility versus effective vertical field (E_{EFF}) under compressive and neutral stress along the channel direction at different gate lengths. Uniaxial stress only affects the short channel devices. To extract the Coulomb mobility, we use Matthiessen's rule and assume that the universal mobility curve (UMC) follows the measurement data in the high-field region [4]. In order to verify the accuracy of the extracted Coulomb mobility, we have compared the extracted Coulomb mobility under various UMC (±10%) and the results are almost the same when Q_{inv} is smaller than $5x10^{12}$ cm^{-2} in Fig. 5, at which V_G is about 1.1V.

Fig. 6 shows the Coulomb mobility of the short-channel devices with different stressors under various temperatures. It can be seen that the Coulomb mobility decreases with temperature because slower electrons are more susceptible to bulk Coulomb scattering [13]. Moreover, the Coulomb mobility shows significant stress dependency. In other words, the strain engineering can still be employed to modulate the Coulomb scattering mobility of short-channel NFETs. Fig. 7 shows the stress sensitivity of the short-channel Coulomb mobility at various temperatures. The stress sensitivity decreases as temperature increases. As pointed out in [3], the mobility limited by bulk impurity scattering shows opposite stress sensitivity to the mobility limited by interface scattering. As temperature increases, the importance of interface scattering increases [13]. As a result, the stress dependency of the overall Coulomb mobility decreases.

Fig. 8 shows the fitting result of $\mu_{Coulomb}$ data with first principle 2-D model. Eq. (1) represents the Coulomb mobility model that includes screened and unscreened effect [9]:

$$\mu_{screened} = \frac{\pi\mu_{screened}}{F(\alpha)} \cdot \frac{Z_{sub}}{Z_{inv}}, \mu_{unscreened} = \frac{640\pi^3 h\varepsilon_{si}^2\varepsilon_0^2 k_b T_L}{G(P)m^* e^3 N_a Z_{sub}} \qquad (1)$$

Where *F(a)* and *G(P)* represent the screening function and the correction factor for repulsive Coulombic potential respectively.

Fig. 9 shows the enhancement of screened and unscreened $\mu_{Coulomb}$ when m* is reduced 20% by applying tensile stress along <110> channel direction on NFETs. The screened $\Delta\mu_{Coulomb}$ is +13% higher than the unscreened $\Delta\mu_{Coulomb}$. This means the bulk screening effect also has strain dependency. It is plausible that the strained device has thinner inversion thickness due to subband splitting effect [3] and better bulk screening effect caused by higher Q_{inv}, as explained in the inset of Fig. 10. Fig. 10 shows that +13% $\mu_{Coulomb}$ is enhanced by +10% Q_{inv} due to higher V_G bias and better screening effect. Our Si data also shows that Q_{inv} is increased +7% at the same V_G bias when 14% μ is enhanced by tensile stress. The finding supports our hypothesis of the stress dependence of the bulk screening effect.

CONCLUSIONS

We have conducted a comprehensive investigation of stress dependency on $\mu_{Coulomb}$ in short channel strained nMOSFETs. Strong temperature dependency on stress dependence of $\mu_{Coulomb}$ is observed because the interface scattering counteracts the stress sensitivity of the bulk charge scattering. The electron screening effect on bulk charge also shows stress dependence because electron density is engineered by the stain-induced subband splitting effect.

ACKNOWLEDGEMENTS

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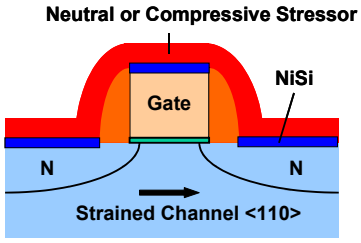

Fig. 1. MOSFET schematic with neutral and compressive stressor.

$\Delta\mu_{Coulomb}$ (Compressive vs Neutral)	+:Enhancement -:Degradation =:No sensitivity	
Mechanism/Scattering Source	N_a (Bulk Charge)	N_{it} (Interface Charge)
Scattering Effect	- (a), m* ↑	+ (b), Z_{inv} ↑
Screening Effect	- (c), Q_{inv}↓	= (d) , no effect @ High N_a

NFET <110> Channel Direction; $\Delta\mu_{Coulomb}=\mu_{Coulomb\_Compressive}-\mu_{Coulomb\_Neutral}$

Table I. Summary table of stress dependence of Coulomb mobility limited by different mechanisms and scattering sources: (a) $\mu_{Coulomb}$ degradation due to higher effective mass (m*) (b) $\mu_{Coulomb}$ enhancement due to thicker inversion layer thickness (Z_{inv}) (c) $\mu_{Coulomb}$ degradation due to lower electron density (d) Minor stress sensitivity on $\mu_{Coulomb}$ due to Quantization effect caused by high N_a.

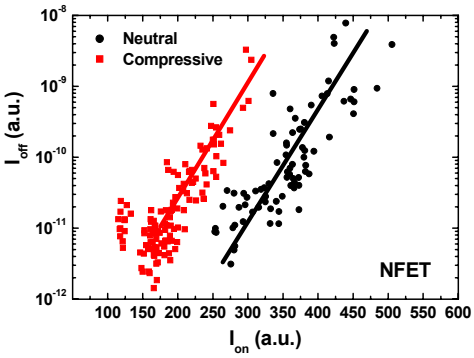

Fig. 2. NFET Ion-Ioff characteristic with neutral and compressive stressor.

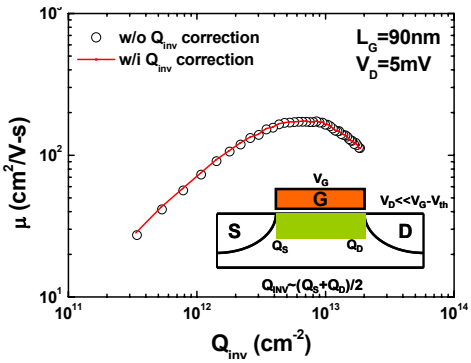

Fig. 3. Extracted mobility by considering spatial distributions of Q_{inv}. (Inset: Spatial distribution due to V_D)

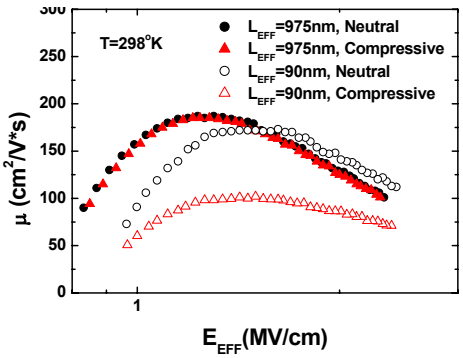

Fig. 4. Extracted short-channel mobility shows significant dependence on the uniaxial stressor applied.

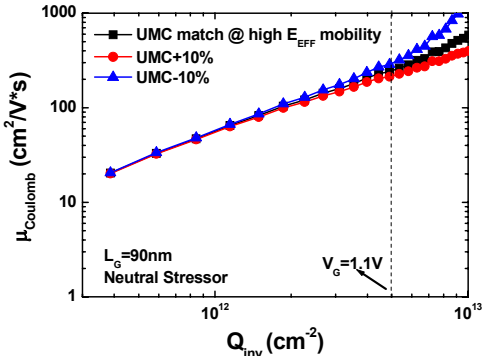

Fig. 5. Varied the UMC (Universal Mobility Curve) by ±10% to verify the accuracy of the extracted Coulomb mobility

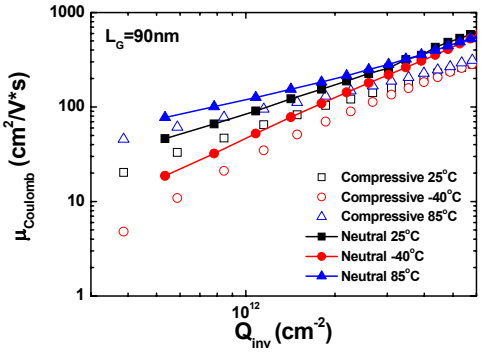

Fig. 6. Coulomb mobility for short-channel devices with different stressors under various temperatures.

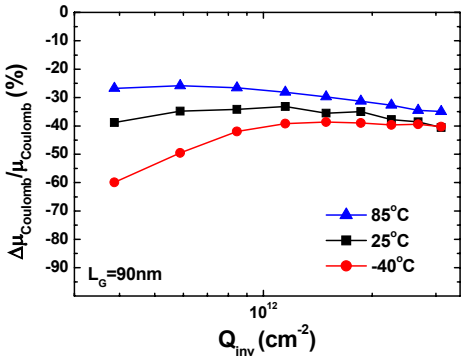

Fig. 7. The stress sensitivity of Coulomb mobility under various temperatures. The $\Delta\mu_{Coulomb}$ represents $\mu_{Coulomb\_strain}$- $\mu_{Coulomb\_neutral}$.

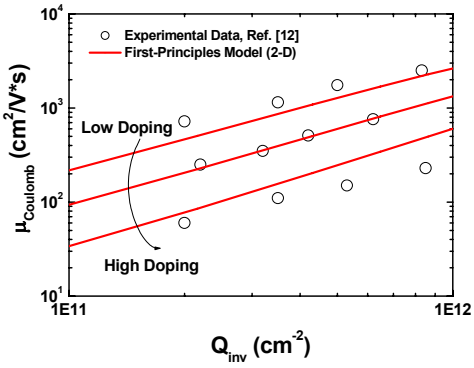

Fig. 8. Coulomb mobility versus Q_{inv} with different bulk concentrations. It shows model fits well with published data [12]. Both screened and unscreened Coulombic scattering effects are included in this model

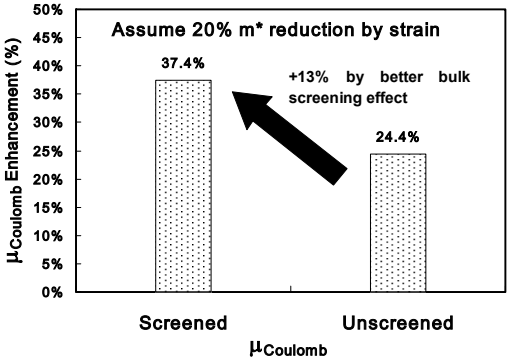

Fig. 9. Screened and unscreened $\mu_{Coulomb}$ enhancement after 20% m* reduction. The prior one shows +13% better than the latter one because of better screening effect by strain.

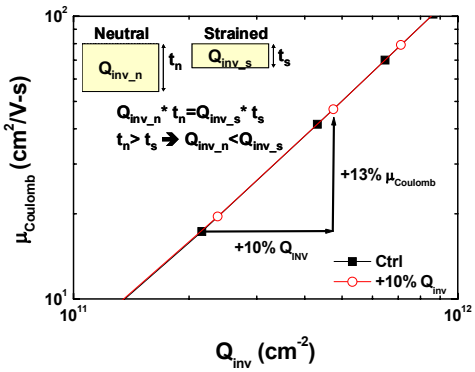

Fig. 10. Coulomb mobility versus Q_{inv}. 10% higher Q_{inv} improves 13% $\mu_{Coulomb}$ due to better bulk screening effect. (Inset: Strain caused thinner inversion layer and then higher Q_{inv})