Experimental Investigation of Surface-Roughness-Limited Mobility in Uniaxial Strained pMOSFETs

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***Abstract*—This letter provides an experimental assessment of surface-roughness-scattering-limited mobility (μ_{SR}) under process-induced uniaxial strain and compares the strain sensitivity between μ_{SR} and phonon-scattering-limited mobility (μ_{PH}). By an accurate split C–V mobility extraction method, the μ_{SR} of short-channel pMOSFETs was extracted at an ultralow temperature to suppress the phonon scattering mechanism. Our result indicates that μ_{SR} has stronger stress sensitivity than μ_{PH}. Furthermore, the surface roughness mobility enhancement tends to increase as the vertical electric field increases. Our experimental findings confirm the previously reported results based on simulations.**

***Index Terms*—MOSFET, strain silicon, surface-roughness-limited mobility, uniaxial.**

I. Introduction

STRAIN technology has been considered as a key process knob beyond 90-nm technology [1]. It is known that strain can improve phonon-scattering-limited mobility (μ_{PH}) by reducing intervalley phonon scatterings and effective conduction mass [2]. Whether strain can improve the surface-roughness-limited mobility (μ_{SR}) is still not clear and demands more experimental investigations. Recently, the biaxial strain dependence of μ_{SR} has been examined by Bonno *et al.* [3] and Zhao *et al.* [4]. These studies have shown that μ_{SR} has strong strain sensitivity for both NFETs and PFETs due to surface morphology engineering with biaxial strain. The temperature dependences of hole mobility by mechanical uniaxial strain [5] and process-induced uniaxial strain [6] have also been studied experimentally. However, the temperature range was higher than 87 K, and the phonon scattering mechanism was not fully suppressed. To investigate the uniaxial strain dependence of surface roughness mobility, it is necessary to extract mobility with temperature down to 20 K to suppress the phonon scattering mechanism.

In this letter, we report our findings on the impact of process-induced uniaxial strain on the μ_{SR} of short-channel pMOSFETs with temperature down to 20 K.

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II. Experimental Setup

The pMOSFETs with channel direction $\langle 110 \rangle$ under neutral, tensile, and compressive uniaxial contact etch-stop layer [6] were investigated. In this study, the carrier mobility of PMOS devices with $L_{EFF} = 95$ nm and a conventional silicon oxynitride gate was examined. The equivalent oxide thickness is about 17 Å. The estimated stress is -2.8 GPa for a compressive film and $+1.6$ GPa for a tensile film. The drain bias condition is -5 mV.

Split C–V measurement [7], [8] was used to characterize the inversion charge density (Q_{inv}). After the gate-to-channel capacitance with a floating bulk terminal (C_{gc}) was calibrated by considering the parasitic components such as overlap capacitance and fringing capacitance [9], [10], Q_{inv} was obtained by integrating the entire C_{gc} curve from a flatband voltage [11].

Since external resistance (R_{sd}) is crucial to the mobility extraction for short-channel devices [12], [13], the intrinsic drain current (I_d) was calibrated by considering the series-resistance effect [14]. The R_{sd} values considered constant as a function of temperature are 201, 208, and 185 $\Omega \cdot \mu$m for neutral, compressive, and tensile stressors, respectively. The physical polygate length (L_{PHY}) was obtained by inline SEM measurement. The LDD overlap region under the gate (L_{OV}) was extracted by the split C–V method at $V_G = 1$ V [15]. The effective channel length (L_{EFF}) can then be derived by subtracting L_{OV} from L_{PHY}. Finally, the carrier mobility can be extracted [6].

In order to extract the surface roughness mobility μ_{SR}, cryogenic temperature measurements were carried out using liquid He as a cooling source. The measurement temperature ranges from 20 to 300 K. HP4156 and HP4285 were adopted to measure the I–V and C–V characteristics.

III. Results and Discussion

Fig. 1 shows the corresponding carrier mobility versus vertical electric field (E_{EFF}) with various temperatures. It can be seen that, under high E_{EFF}, the mobility tends to increase as the temperature decreases due to suppressed phonon scattering. At a temperature lower than 60 K, the mobility at high E_{EFF} saturates because the phonon scattering mechanism is fully suppressed. In other words, the mobility at high E_{EFF} within this temperature range can be viewed as the surface-roughness-limited mobility.

Fig. 2 shows the extracted carrier mobility versus temperature at $E_{EFF} = 1.6$ MV/cm for various stressors. It can be

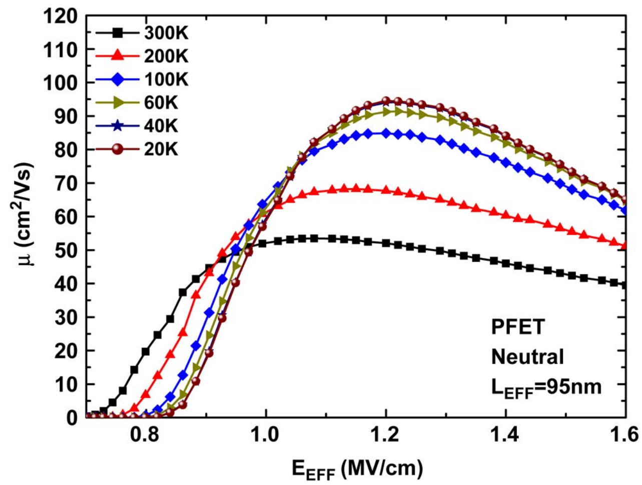

Fig. 1. Extracted carrier mobility versus vertical electric field under various temperatures.

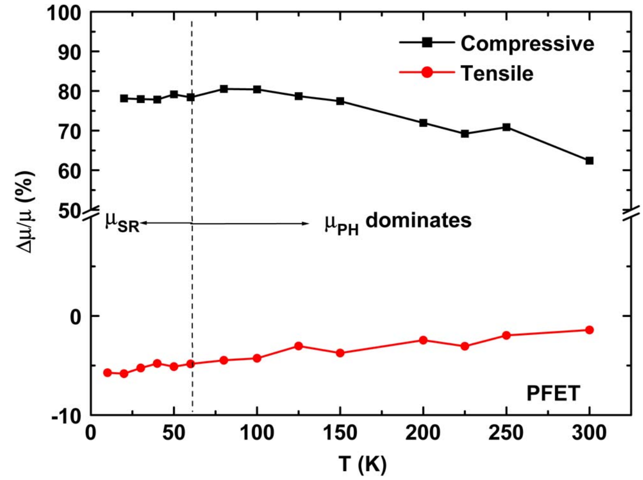

Fig. 3. Mobility enhancement percentage $(\Delta\mu/\mu)$ versus temperature with compressive and tensile stressors.

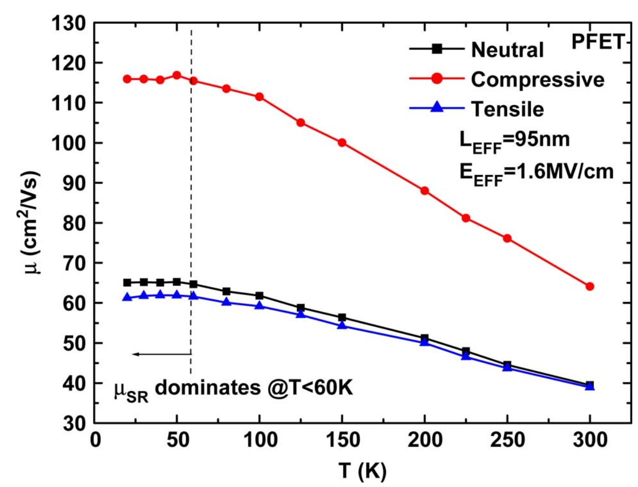

Fig. 2. Extracted carrier mobility at $E_{\mathrm{EFF}} = 1.6$ MV/cm with various stressors. μ_{SR} dominates the total mobility for temperature < 60 K.

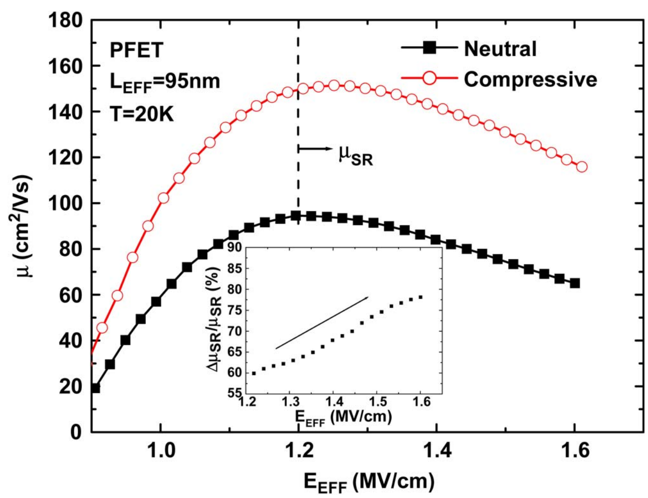

Fig. 4. Extracted carrier mobility versus vertical electric field at 20 K for the neutral and compressive stressors. (Inset) Surface roughness mobility enhancement increases as E_{EFF} increases.

seen that the compressive uniaxial strain results in a significant mobility enhancement due to band engineering and carrier repopulations [2]. In addition, μ_{SR} dominates the total mobility for temperature < 60 K for all kinds of stressors. Fig. 3 shows the mobility enhancement percentage $(\Delta\mu/\mu)$ versus temperature with compressive and tensile stressors. As the temperature decreases, it can be observed that the mobility enhancement increases and saturates at temperature < 60 K where surface roughness scattering dominates. It indicates that μ_{SR} has stronger stress sensitivity than μ_{PH}. Furthermore, the surface roughness mobility enhancement tends to saturate and shows little sensitivity to temperature. It is worth noting that our experimental results are consistent with the reported results by simulations [5], [16], [17]. Specifically, it was reported in [16] that the scattering rate with interfacial roughness can be reduced by smoother interfaces in biaxial strained NFETs. In addition, the atomic scale model in [17] also indicates weaker surface scattering potential in strained Si due to the nature of primitive defects. For the uniaxially strained PFET case, it is plausible that the lighter effective conduction mass [5] induced by compressive strain may result in μ_{SR} enhancement.

Fig. 4 shows the extracted carrier mobility versus effective vertical electric field (E_{EFF}) for neutral and compressive stressors at 20 K. Within this temperature range, both the Coulomb scattering and surface roughness scattering mechanisms are crucial in the determination of the overall carrier mobility. It can be seen that the mobility is dominated by the surface roughness scattering mechanism for E_{EFF} higher than 1.2 MV/cm. The inset of Fig. 4 shows that μ_{SR} enhancement increases with E_{EFF} in the high-E_{EFF} regime where the carrier mobility is dominated by surface roughness scatterings.

IV. Conclusion

By accurate split C–V mobility extraction, the strain dependence of μ_{SR} in short-channel pMOSFETs has been investigated under cryogenic temperatures. Our measured data indicate that μ_{SR} can be significantly enhanced by the uniaxial compressive strain. Furthermore, μ_{SR} has higher strain dependence than the phonon-scattering-limited mobility (μ_{PH}). Our experimental results confirm the previously reported results based on simulations.

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