Enhanced Temperature Dependence of Phonon-Scattering-Limited Mobility in Compressively Uniaxial Strained pMOSFETs

William Po-Nien Chen, Jack Jyun-Yan Kuo, *Student Member, IEEE*, and Pin Su, *Member, IEEE*

***Abstract*—This paper investigates the temperature dependence of phonon-scattering-limited mobility μ_{PH} for advanced short-channel strained pMOS devices. By using the split CV method and Matthiessen's rule, surface-roughness-limited mobility μ_{SR} and μ_{PH} are successfully decoupled. This paper indicates that the temperature sensitivity of μ_{PH} is proportional to $T^{-1.75}$ for a neutral stressor and becomes higher when compressive strain is applied. It is explained by the higher optical phonon energy induced by uniaxially compressive strain. Our new findings may also explain the previously reported higher temperature sensitivity of drain current present in uniaxial strained pMOSFETs.**

***Index Terms*—Cryogenic temperature, MOSFET, phonon-scattering-limited mobility, strain silicon, uniaxial.**

I. Introduction

Uniaxial strained-Si technology is a key knob to boost transistor performance in state-of-the-art CMOS technology [1], [2]. The temperature dependence of strain-enhanced mobility is of fundamental importance and may provide insights for the underlying mechanisms responsible for performance enhancement. Recently, several studies have revealed that the temperature sensitivity of drain current for pMOSFETs is increased by uniaxially compressive strain [3]–[6]. However, the underlying mechanism is still not clear and merits investigation.

In this paper, through cryogenic temperature measurement to decouple surface-roughness-limited mobility μ_{SR} and phonon-scattering-limited mobility μ_{PH}, we investigate the impact of uniaxial strain on the temperature dependence of phonon-scattering-limited mobility in nanoscale pMOSFETs.

II. Experimental

In this paper, pMOSFETs with channel direction $\langle 110\rangle$ under neutral and compressive uniaxial contact-etch-stop layer (CESL) [7] were investigated. The compressive strain is ~ -2.8 GPa. The equivalent oxide thickness (EOT) is about 17 Å, whereas the electrical EOT taking into account the quantum–mechanical and polydepletion effects is around 23 Å. The carrier mobility of pMOS devices with $L_{\mathrm{EFF}} =$ 95 nm and effective channel doping $\sim 2\times 10^{18}$ cm^{-3} was examined. The drain bias condition was 5 mV. Since external resistance R_{sd} is crucial to mobility extraction for short-channel devices [8], [9], the BSIM R_{sd} method [10] was adopted to extract the external resistance based on the I–V characteristics. The ideal drain current can then be derived from

$$I_d(\mathrm{int}) = \frac{\mathrm{I_d(ext)}}{1-\mathrm{I_d(ext)}\times\frac{\mathrm{R_{sd}}}{\mathrm{V_d}}} \tag{1}$$

where $I_d(\mathrm{int})$ represents the intrinsic drain current, and $I_d(\mathrm{ext})$ represents the extrinsic drain current that includes the R_{sd} effect.

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 CV method [11], [17]. Effective channel length L_{EFF} can then be derived by subtracting L_{OV} from L_{PHY}. Finally, the carrier mobility can be extracted. E_{EFF} is extracted by

$$E_{\mathrm{eff}} = \frac{Q_b + \eta\cdot Q_{\mathrm{inv}}}{\varepsilon_{\mathrm{Si}}} \tag{2}$$

where η is equal to 1/3 [16], and $\varepsilon_{\mathrm{Si}}$ is the permittivity of Si. Q_{inv} and Q_b can be obtained by integrating the CV curves from the split CV measurement [11]. The applied maximum gate-to-source bias is -2.5 V.

In order to extract surface-roughness mobility μ_{SR}, cryogenic temperature measurements were carried out using liquid He as the cooling source. The measurement temperature ranged from 20 K to 300 K. HP4156 and HP4285 were adopted to measure the transistor IV and CV characteristics.

III. Results and Discussion

Fig. 1 shows the measured carrier mobility under compressive and neutral uniaxial strain with temperature ranging from 20 K to 60 K. It is known that the phonon-scattering mechanism can be suppressed and the surface-roughness-scattering mechanism may dominate within this temperature range (particularly for $E_{\mathrm{EFF}} > 1.3$ MV/cm) [12]. It is shown that μ_{SR} shows little temperature dependence, which is consistent with the reported data in the past [12], [13].

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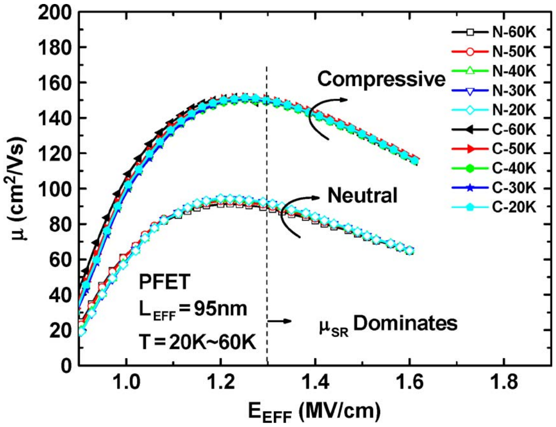

Fig. 1. Measured total mobility with temperature ranging from 20 K to 60 K for pMOSFETs with neutral and compressive uniaxial stressors. Surface-roughness mobility μ_{SR} tends to dominate as $E_{\mathrm{EFF}} > 1.3$ MV/cm and is independent of temperature.

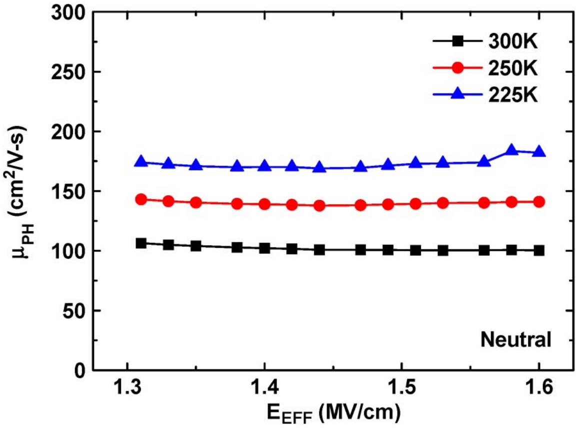

Fig. 2. Extracted phonon-scattering-limited mobility for neutral stressors at $T = 225$ K, 250 K, and 300 K, respectively.

In order to extract μ_{PH}, it is assumed that μ_{SR} is independent of temperature [12], [13], and then, the Matthiessen's rule can be adopted, i.e.,

$$\mu_{\mathrm{PH}}^{-1}(T) = \mu_{\mathrm{Total}}^{-1}(T) - \mu_{\mathrm{SR}}^{-1}(T = 20\ \mathrm{K}) \tag{3}$$

where μ_{Total} is the total mobility, including impurity, phonon, and surface-roughness-scattering mechanisms, and μ_{SR} (20 K) is the surface-roughness mobility at E_{EFF} larger than 1.3 MV/cm. Fig. 2 shows the extracted μ_{PH} at 300 K, 250 K, and 225 K for neutral stressors. It is shown that μ_{PH} increases with decreasing temperature because of decreased phonon-scattering rate [12].

Fig. 3 shows the E_{EFF} dependence of μ_{PH} and μ_{SR}. Extracted μ_{PH} and μ_{SR} are proportional to $E_{\mathrm{EFF}}^{-1.3}$ and $E_{\mathrm{EFF}}^{-0.3}$, respectively, which is consistent with the reported data in the past [12], [13]. Fig. 4 shows the temperature dependence values of μ_{PH} ($\mu_{\mathrm{PH}} \propto T^{-\alpha}$) versus E_{EFF} for neutral and compressive stressors. It is shown that α is close to 1.75 for the neutral stressor, which is consistent with the reported data in the literature [12]. Fig. 4 also shows that, with compressive uniaxial strain, the temperature sensitivity of μ_{PH} is increased ($\alpha \approx 2.3$).

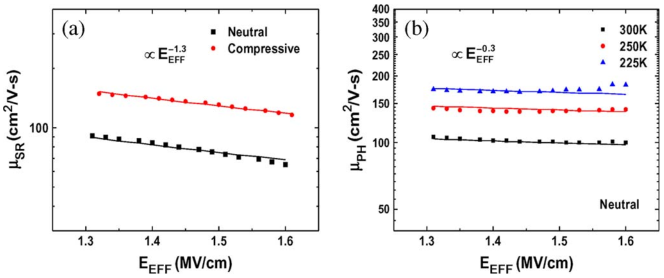

Fig. 3. E_{EFF} dependence of μ_{SR} and μ_{PH} in (a) and (b). Extracted μ_{SR} and μ_{PH} are proportional to $E_{\mathrm{EFF}}^{-1.3}$ and $E_{\mathrm{EFF}}^{-0.3}$, respectively.

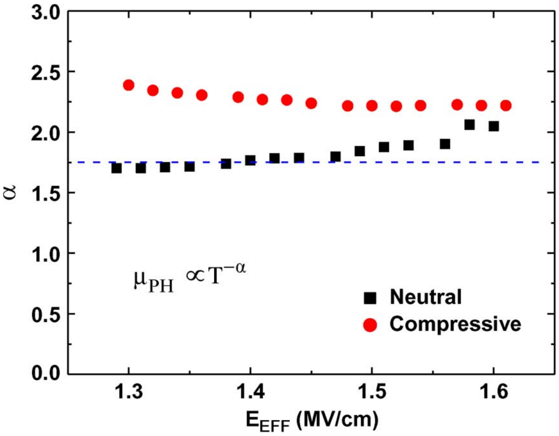

Fig. 4. Temperature dependence of μ_{PH} for neutral and compressive stressors. The α of the neutral stressor is close to 1.75, whereas with the compressive stressor, the α value further increases to around 2.3 .

It is plausible that the observed strain dependence of α in Fig. 4 results from strain-engineered intervalley scattering of optical phonons [14], [15]. The temperature dependence of optical phonon mobility can be expressed as [15]

$$\mu_o = A_o T^{-\frac{1}{2}} e^{\frac{\hbar\omega_o}{kT}} \tag{4}$$

where A_o is a constant, T is the temperature, k is Boltzmann's constant, and $\hbar\omega_o$ represents the optical phonon energy. By the differentiation of (4) with respect to T

$$\frac{\delta \log \mu_o}{\delta \log T} = -0.5 - \frac{\hbar\omega_o}{kT}. \tag{5}$$

It is shown that the temperature sensitivity of the optical phonon mobility depends on optical phonon energy $\hbar\omega_o$. The schematic plot of the $E-k$ band diagram in Fig. 5 shows the impact of uniaxial compressive strain on $\hbar\omega_o$. The strain induces the light-hole (LH) and heavy-hole band splits and most of the holes repopulate into the LH band [14]. In other words, $\hbar\omega_o$ is increased due to band splitting as the compressive strain is applied. Therefore, the α value is increased (see Fig. 4) for the compressively strained pMOSFETs.

From previous reports [3]–[6], it has been found that the temperature sensitivity of drain current for the compressively strained pFET is larger than that of the unstrained counterpart. Our new finding in this paper, i.e., the strain-enhanced temperature sensitivity of μ_{PH}, has suggested a plausible mechanism

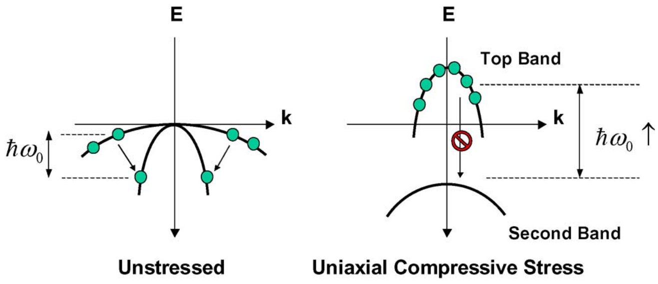

Fig. 5. Schematic plot of the $E{-}k$ energy band diagram under a uniaxial compressive stressor in pFET. Optical phonon energy $\hbar\omega_0$ may increase when compressive uniaxial strain is applied.

responsible for these observations. It also provides insights for future mobility scaling using advanced strain technologies.

IV. CONCLUSION

We have investigated the temperature dependence of μ_{PH} for advanced short-channel strained pMOS devices. By using the split CV method and Matthiessen's rule, μ_{SR} and μ_{PH} are successfully decoupled. This paper indicates that the temperature sensitivity of μ_{PH} is proportional to $T^{-1.75}$ for the neutral stressor and becomes higher when compressive strain is applied. It is explained by the higher optical phonon energy induced by uniaxially compressive strain. Our new findings may also explain the previously reported higher temperature sensitivity of drain current present in uniaxial strain pMOSFETs.

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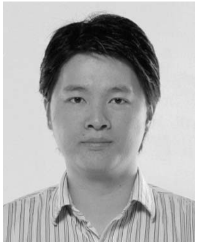

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