Performance-Augmented CMOS Using Back-End Uniaxial Strain

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As scaling becomes increasingly expensive, alternative methods and materials are being explored to enhance device speed/performance. Introducing strain into silicon particularly by the pseudomorphic growth of Si on SiGe alloys has been shown to improve the mobility of both n and p-channel devices [1,2]. In this approach, the induced strain is biaxial and is introduced in the front-end of the process. Subsequent processing must contend with a low thermal budget to prevent Ge migration. Recently, a new back-end approach has been proposed [3] which circumvents these limitations by applying uniaxial strain to wafers/dies after the IC process is completed. Uniaxial strained-Si has advantages over biaxial strained-Si. Compared to bulk silicon it has a reduced band gap, reduced in-plane effective mass and hence improved conduction. The work function is altered and contact potentials are reduced. The level of uniaxial strain required is less than biaxial strain, for the same improvement factor [4].

In this paper we report the first detailed electrical characterization of uniaxially-strained fully-depleted silicon-on-insulator (FD-SOI) n and p-channel MOSFETs. Using the back-end approach, an in-plane, tensile strain was applied to the FD SOI MOSFETs after device manufacture. Dies were thinned to membrane dimensions and then affixed to curved substrates. The die transfer process minimizes edge effects and spurious membrane behavior. The FD-SOI MOSFETs were fabricated at Lincoln Labs using 0.25 µm technology. Gate oxide thickness was approximately 6.5 nm and the silicon layer thickness was approximately 50 nm. MOSFETS with gate lengths ranging between 0.2 to 8 µm on 8 µm wide devices were tested in these dies for both n and p-channel devices. Coplanar microwave pads with 100 µm pitch were used for S-parameter measurements of the n-MOSFETS.

The strain levels described here ranged to only 0.03 % while strains up to 0.07 % have now been completed for test. This is small in contrast to typical biaxial strains which range from 1% to 2%. Despite the low value of strain, we observe consistent and notable increase in the low-field mobility with small shift in threshold voltage, analyzed following the approach of Sanchez, et al. [5]. Electron effective mobility increases with the perpendicular strain and decreases with effective vertical field E_{eff} due to phonon scattering ($\mu_{eff} \sim E_{eff}^{-0.3}$) [4]. When E_{eff} is high, surface roughness scattering dominates ($\sim E_{eff}^{-2}$). While for holes, when E_{eff} is larger than 0.3 MV/cm, surface roughness begins to control the hole mobility ($\sim E_{eff}^{-1}$). Current gain cut-off frequency showed some substantial enhancement (factor ~2x) on some devices, but others were observed to decrease. This is a recent result currently under investigation.

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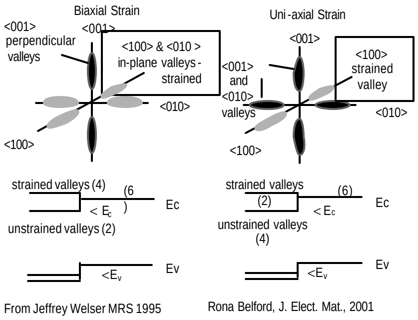
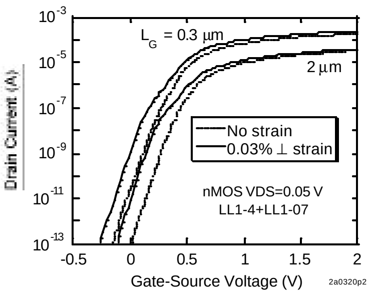
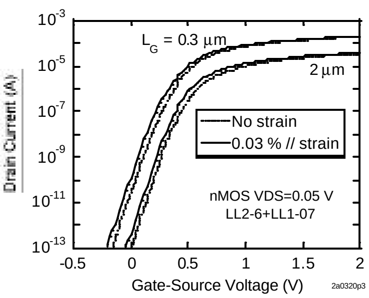


Figure 1. Biaxial vs. uniaxial strain in Si

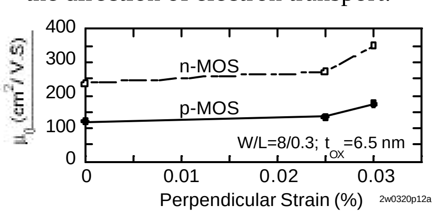


(a)

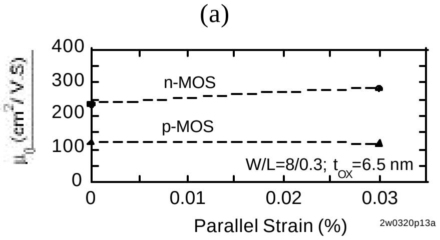


(b)

Figure 2. Fully-depleted SOI n-MOSFETs measured before and after uniaxial tensile strain (a) ⊥ and (b) // to the direction of electron transport.

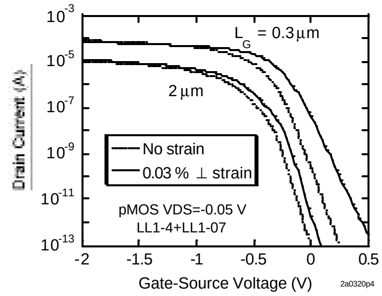


(a)

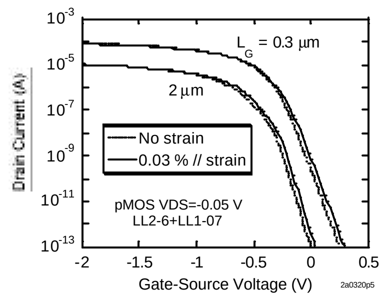


(b)

Figure 3. Strain dependence of the low field electron mobility (a) perpendicular and (b) parallel to the direction of electron transport.

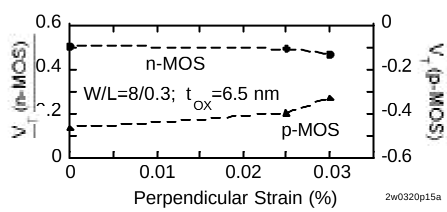


(a)



(b)

Figure 4. Fully-depleted SOI p-MOSFETs measured before and after uniaxial tensile strain (a) ⊥ and (b) // to the direction of electron transport.



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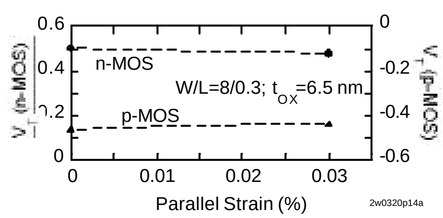
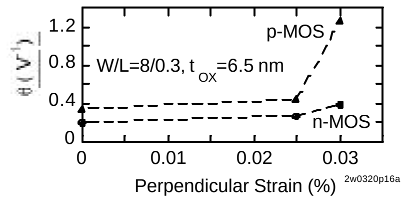
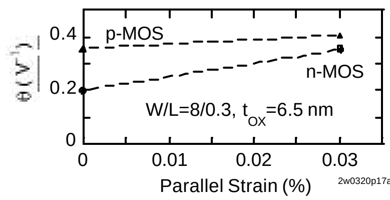


(b)

Figure 5. Dependence of threshold voltage on the orientation of uniaxial strain for n- and p-MOSFETs.



(a)



(b)

Figure 6. Dependence of the mobility degradation parameter, θ, on the orientation of uniaxial strain for n- and p-MOSFETs.

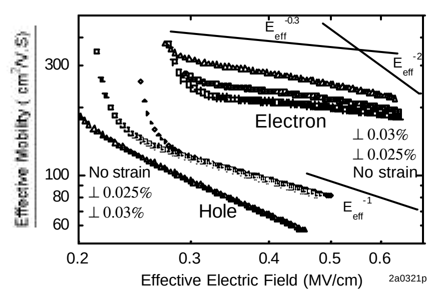


Figure 7. Electric field dependence of mobility as a function of uniaxial strain perpendicular and parallel to the electron transport direction

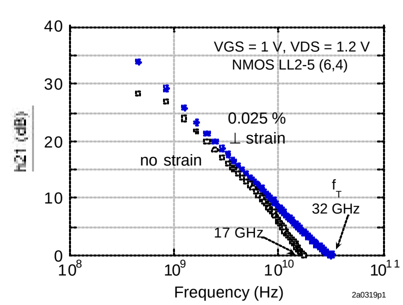


Figure 8. Comparison of 0.25 µm n-MOSFET current gain frequency response before and after uniaxial tensile strain oriented perpendicular to the direction of electron transport.