Mobility Enhancement of Two-dimensional Hole Gas in an $In_{0.24}Ga_{0.76}As$ Quantum Well by <110> Uniaxial Strain

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Achieving a high-performance p-FET remains one of the grand challenges that stand on the way of a future complementary CMOS technology using InGaAs [1]. A critical problem is the low hole mobility in this material. In this work, we experimentally study the feasibility of hole mobility enhancement through <110> uniaxial strain added to the -1.7% built-in biaxial strain of an $In_{0.24}Ga_{0.76}As$ quantum well (QW) on GaAs. The impact of uniaxial strain on hole mobility (μ_h) and concentration (p_s) was measured through Hall measurements. Strain-induced changes in μ_h and p_s are found to arise from a combination of piezoelectric field and valence band dispersion changes. The highest μ_h change reaches 12% per 100 MPa stress.

Our experiments studied Hall bars based on a heterostructure with a 9 nm biaxially-strained QW (Fig. 1). Our heterostructure and process yields p-channel FETs with satisfactory characteristics (Fig. 2). A chip-bending apparatus [2] combined with a pair of permanent magnets (Fig. 3) was used to perform Hall measurements with various levels of stress (σ) applied to the Hall bars. The configurations of Hall bars and stress orientations are illustrated in Fig. 3.

The change in R_{sh} (Fig. 4) depends on the stress orientation relative to both current flow and crystal direction. The observed behavior of ΔR_{sh} is due to a combination of anisotropic change in μ_h (Fig. 5 and 6) and p_s (Fig. 7). Δp_s is almost entirely determined by the crystallographic orientation of the applied stress. This is due to the piezoelectric effect. When adding Schottky barrier height change due to the hydrostatic strain component [2], good agreement with experiments is predicted by Poisson-Schrodinger simulations (dashed lines in Fig. 7).

The change in μ_h (Fig. 5 and 6) does not have a simple relationship to crystalline orientation of stress. Two effects are mainly responsible for $\Delta\mu_h$: 1) valence band (VB) warping due to uniaxial stress; 2) VB bending caused by the piezoelectric field (P_z). Effect 1) has been seen in Si and Ge. [3] The consequence of this effect is that compressive $\sigma_{//}/\sigma_{\perp}$ increases/decreases μ_h. Tensile stress shows the opposite effect. Effect 2) is due to the fact that the VB dispersion relation depends on the quantization in QW [4]. Band bending due to P_z changes the quantization and therefore the VB dispersion relation. Using *k.p* method, we simulated the VB structure in our QW including the external uniaxial strain, built-in biaxial strain and P_z. (Fig. 8) We calculated the averaged transport effective mass (m^*), a key factor that impacts μ_h [5], by following the treatment of nonparabolic bands in [6]. Due to the nonparabolicity of VB, m^* slowly increases with p_s (Fig. 9) in agreement with experiments [7]. However, Δm^* due to VB structure change dominates. In this there is a pronounced difference between the effect of uniaxial strain along the two <110> directions. (Fig. 9) This is because the P_z-induced Δm^* opposes or enhances the stress-induced Δm^* depending on crystalline orientation of stress. In agreement with our data, the simulation predicts that $m^*_{//}$ is more sensitive to $\sigma_{[-110]}$ than to $\sigma_{[110]}$. (Fig. 10) We notice that unlike the simulated $\Delta m^*_{\perp}$, $\Delta\mu_{\perp}$ is also more sensitive to $\sigma_{[-110]}$ than to $\sigma_{[110]}$. We tentatively attribute this to anisotropic structural properties along the [110] and [-110] directions observed in strained InGaAs layers [8, 9].

In sum, we experimentally studied uniaxial stress effect on a biaxially-strained $In_{0.24}Ga_{0.76}As$ QW. The hole concentration and hole mobility change as a result of piezoelectric field and valence band dispersion changes. A unique effect suggested by our simulations and experiments is that the piezoelectric field can enhance or supress mobility enhancement. Therefore, there exists a preferred crystal direction of stress for μ_h enhancement: our experiments suggest this direction is [-110] with $\pi_{//} = 1.2\times10^{-10}$ cm^2/dyn and $\pi_{\perp} = 0.7\times10^{-10}$ cm^2/dyn.

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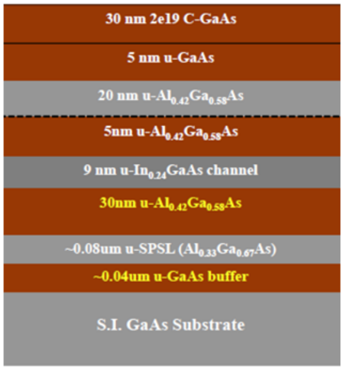

Fig. 1. Cross section of the heterostructure in this study.

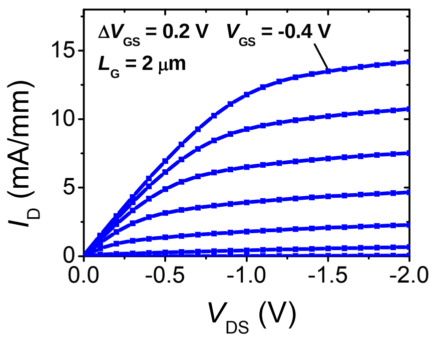

Fig. 2. Typical output characteristics of a p-channel FET with L_G=2 μm.

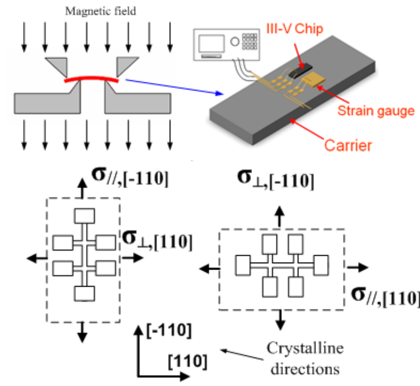

Fig. 3. Measurement setup and notation for stress and hole transport directions.

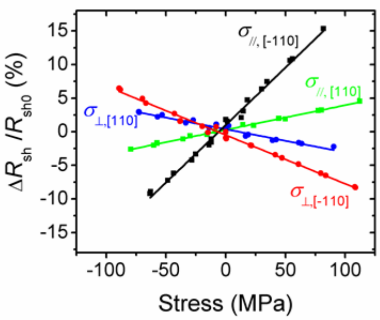

Fig. 4. Change of sheet resistance (R_{sh}) with <110> uniaxial stress.

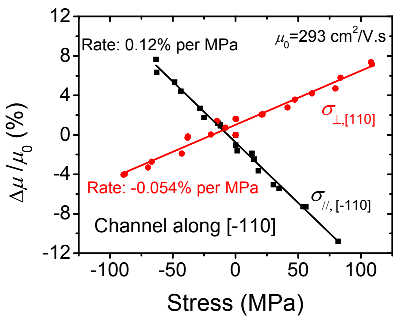

Fig. 5. Mobility change with <110> uniaxial stress in [-110] Hall bar.

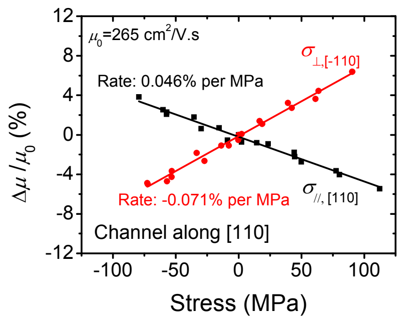

Fig. 6. Mobility change with <110> uniaxial stress in [110] Hall bar.

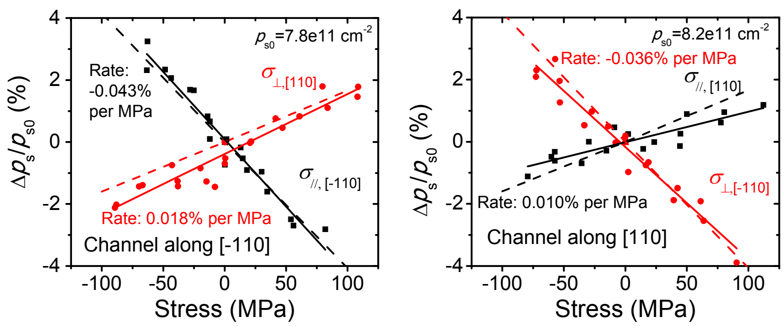

Fig. 7. Sheet hole concentration change with <110> uniaxial stress in (left) [-110] and (right) [110] Hall bar.

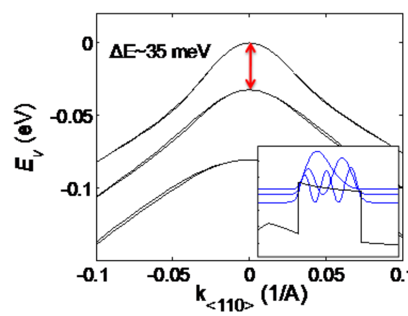

Fig. 8. Valence band structure in 9 nm $In_{0.24}Ga_{0.76}As$ QW with -1.7% biaxial strain. The inset shows the QW and wavefunctions of the top 3 subbands.

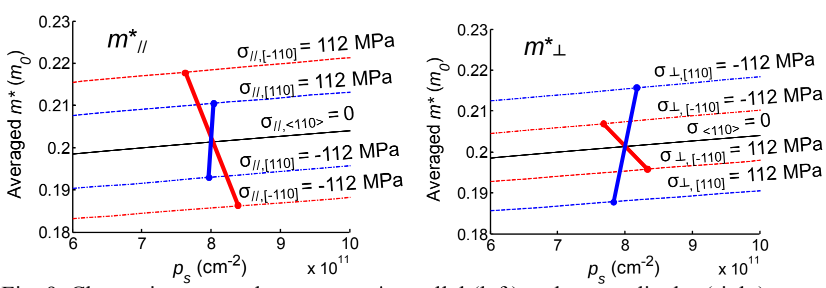

Fig. 9. Change in averaged transport m^* parallel (left) and perpendicular (right) to applied <110> uniaxial stress as a function of p_s. The thick solid lines in red (for [-110]) and blue (for [110]) represent the trajectory of Δm^* with stress.

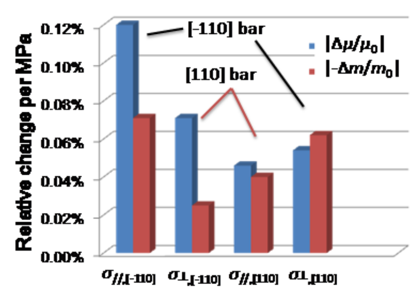

Fig. 10. Comparison between experimental mobility changes and simulated effective mass changes with uniaxial stress.

References: [1] D.-H. Kim, IEDM 2009; [2] L. Xia, IPRM, 2010; [3] S. E. Thompson, IEDM, 2004; [4] T. M. Lu, APL, 2008; [5] E. X. Wang, TED, 2006; [6] M. De Michielis, TED, 2007; [7] S. Y. Lin, APL, 1995; [8] K. Rammohan, APL, 1995; [9] S. Lohr, PRB, 2003.