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 ($\mu_h$) and concentration ($p_s$) was measured through Hall measurements. Strain-induced changes in $\mu_h$ and $p_s$ are found to arise from a combination of piezoelectric field and valence band dispersion changes. The highest $\mu_h$ 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 ($\sigma$) 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 $\Delta R_{sh}$ is due to a combination of anisotropic change in $\mu_h$ (Fig. 5 and 6) and $p_s$ (Fig. 7). $\Delta p_s$ 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 $\mu_h$ (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 $\mu_h$. 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 $\mu_h$ [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, $\Delta m^*$ 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 $\Delta m^*$ opposes or enhances the stress-induced $\Delta m^*$ 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 $\Delta m^*_{\perp}$, $\Delta \mu_h$ 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 suppress mobility enhancement. Therefore, there exists a preferred crystal direction of stress for $\mu_h$ enhancement: our experiments suggest this direction is [-110] with $\pi_{//} = 1.2 \times 10^{-10}$ cm$^2$/dyn and $\pi_{\perp} = 0.7 \times 10^{-10}$ 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 $L_G=2 \ \mu m$.

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 $\Delta m^*$ with stress.

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