Hydrogen Degradation in InP HEMTs

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Abstract

In this work we have investigated the degradation of InP HEMTs due to hydrogen exposure. We show for the first time that there are two independent degradation mechanisms that affect, respectively, the intrinsic and extrinsic portions of the device. Under the gate, H reacts with Ti and creates a TiH compound with a larger lattice that Ti. This induces stress and the resulting piezoelectric effect shifts the threshold voltage, V_T, of the transistor. This mechanism is found to be largely reversible. In the recessed region next to the gate, hydrogen modifies the surface stoichiometry of the exposed InAlAs. This results in a reduction in the sheet carrier concentration underneath. This mechanism is not reversible.

Introduction

Hydrogen degradation in GaAs HEMTs is a serious and well documented reliability concern [1-4]. However very little is known about the H_2 sensitivity of InP HEMTs [3]. Exposure occurs when small amounts of hydrogen outgas from hermetically sealed packages. Over time, hydrogen causes changes in device characteristics, affecting V_T, I_D and g_m. This device degradation results in changes in amplifier gain, and can lead to parametric module failures. A device-level solution to this problem has not been reported.

The extent of the problem has been documented in both GaAs MESFETs and PHEMTs. For example, GaAs PHEMTs measured at 60 °C have shown a decrease in mean-time-to-failure (MTTF) from 10^{11} hr. in pure N_2, to just over 10^4 hours in H_2 partial pressures of only 3 T [2]. Only limited data on InP HEMTs is available, with exposure times less than 20 minutes [3].

While the detailed mechanism by which H_2 degrades operation is not understood, previous researchers have traced the degradation to the presence of Pt in the gate metallization. Pt is known to be a catalyst for H_2, breaking it down into 2H, which then diffuses through the gate [1]. However, Chao *et al.*, showed that degradation also occurred in GaAs PHEMTs fabricated with Ti-only gates, although the failure times were significantly longer than Pt/Ti gate devices [4]. Building on this work, we show for the first time that H_2 in InP HEMTs results in two distinct mechanisms that affect the intrinsic and extrinsic portions of the device independently. Through measurement of device parameters such as V_T and off-state drain-to-gate breakdown voltage, BV_{DG}, which are sensitive to changes in the intrinsic and extrinsic regions, respectively, we are able to unambiguously resolve these independent mechanisms.

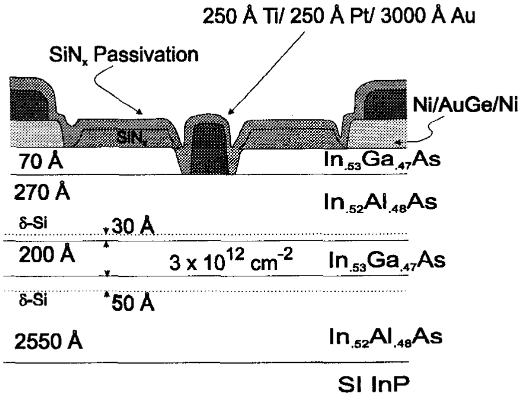

Figure 1: InP HEMT structure used in this work.

Experimental

The InP HEMTs used for this study were fabricated at MIT and feature a selective cap recess, sidewall recess isolation, dielectric-assisted lift-off, Ti/Pt/Au gates and ECR-enhanced, low-temperature Si_3N_4 passivation (Fig. 1). Gate lengths vary from 0.6 μm to 10 μm. On a (100) substrate, devices with gates oriented along the [011], [010] and [01$\bar{1}$] direction were characterized.

Measurements were made in a temperature controlled wafer probe station equipped with a sealed chamber allowing the introduction of N_2 or forming gas (5% H_2 in N_2). All devices underwent a thermal burn-in (230 °C in N_2) until no further ΔV_T was measured, generally about 2 hours. The devices were then annealed unbiased at 200 °C for 3 hours in forming gas, followed by recovery at 200 °C in N_2. For reference, selected devices were annealed in N_2 under identical conditions. Detailed room-temperature characterization was performed pre-anneal, post-anneal and post-recovery. In a subset of devices, ΔV_T was monitored *in situ* at 200 °C as a function of time. We used ΔV_T to assess intrinsic device degradation and ΔBV_{DG} (off-state) to monitor degradation in the extrinsic device [5]. V_T was measured with $V_{DS} = 0.1$ V to sample $n_{s(intr)}$ near the center of the gate. BV_{DG} was measured using the drain-current injection technique with a 1 mA/mm criteria [6].

Results

Under forming gas, V_T shifted negative for all devices (Fig. 2), consistent with studies on 0.1 μm InP HEMTs [3]. While the measured V_T shifts are small, they are statistically significant when compared to the N_2 control. ΔV_T shows an inverse L_G behavior. Fig. 3 shows that there is also an orientation dependence in ΔV_T, where the [011] devices shifted the most, followed by the [010], and then the [01$\bar{1}$]. After subsequent N_2 annealing V_T mostly recovers to its pre-forming gas anneal value, and the V_T difference among different orientations is nearly eliminated.

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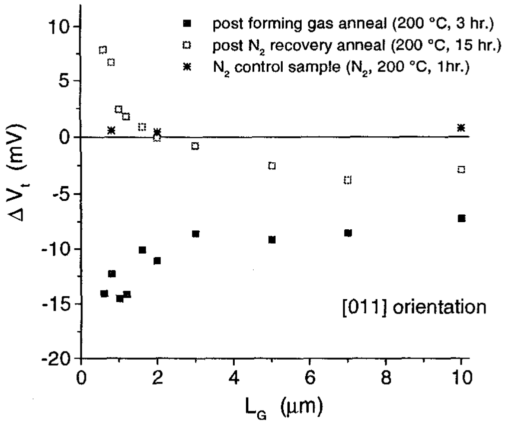

Figure 2: ΔV_T vs. L_G after annealing in forming gas, and after a subsequent anneal in N_2.

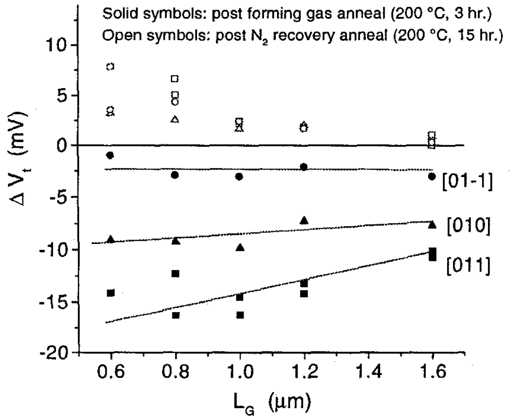

Figure 3: Orientation dependence of ΔV_T as a function of gate length.

BV_{DG} exhibits a strikingly different behavior. After forming gas annealing, BV_{DG} increased on average 0.9 V for all devices, exhibiting no L_G or orientation dependence (Fig. 4). BV_{DG} does not recover after subsequent N_2 annealing.

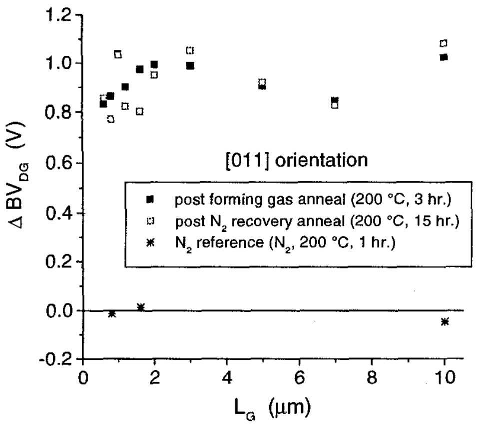

Figure 4: ΔBV_{DG} vs. L_G showing no L_G dependence. ΔBV_{DG} also showed no orientation dependence.

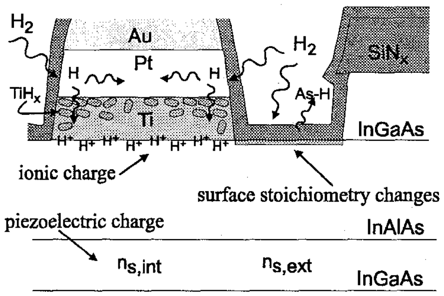

Figure 5: Sketch (not to scale) depicting dominant H_2 effects in InP HEMTs. H_2 is catalyzed by Pt, producing 2H which diffuses laterally through the gate and reacts with Ti to produce TiH [1,4]. The resulting stress induces piezoelectric charges in the transistor, shifting V_T. When the gate becomes saturated, H diffuses down to the semiconductor, resulting in a second V_T drop. In the extrinsic region, H_2 modifies the surface stoichiometry of the InAlAs, possibly producing a cation rich surface through As desorption. This reduces n_s in the extrinsic region, causing BV_{DG} to increase.

Discussion

The distinct behavior of V_T and BV_{DG} leads us to postulate that at least two independent physical mechanisms are at play in the intrinsic and extrinsic portions of the device (Fig. 5). The L_G and orientation dependence of ΔV_T are key signatures of the piezoelectric effect. Chao *et al.* have observed H_2 induced degradation in Ti-only gate PHEMTs [4], which lead them to speculate on the formation of TiH and a change in Schottky barrier height. This explanation should not result in L_G or orientation dependence. Instead, the formation of TiH can affect V_T through induced piezoelectric charges if the gate expands in volume. In fact, the Ti-H phase diagram shows that formation of γ-phase TiH is possible in our experimental conditions. γ-phase TiH has a lattice volume 15% larger than Ti [10]. Forming gas anneals on unpassivated devices show nearly identical ΔV_T behavior, confirming that the gate, and not the passivation layer, is the source of the stress.

The sign of ΔV_T is consistent with calculated piezoelectric charge distributions in GaAs MESFETs for a gate region under compressive stress [8,9]. In addition, we find that the functional L_G dependence of ΔV_T agrees with published data on V_T shifts in GaAs MESFETs as a result of externally applied stress [7] (Fig. 6). Finally, we have confirmed the presence of TiH through Auger measurements on 250 Å Ti/250 Å Pt test samples annealed in forming gas under identical conditions. The amount of TiH was found to decrease after subsequent recovery anneals at 200 °C for 15 hours in N_2 [12,13].

Further insight is obtained by examining the time evolution of ΔV_T, shown in Fig. 7 (in this experiment, V_T was measured at 200 °C). Degradation begins immediately, consistent with behavior reported for gates containing Pt [3,4]. Pt is known to catalyze H_2 into 2H,

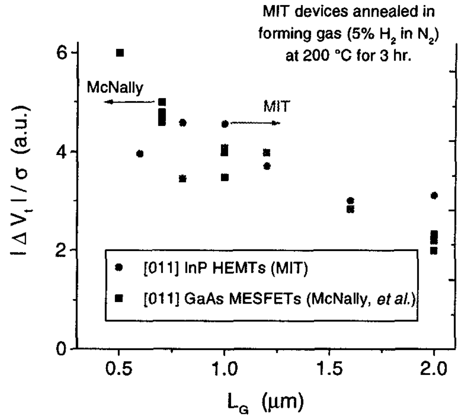

Figure 6: Comparison of ΔV_T vs. gate length for MIT devices and measured data from McNally, *et al.* for [011] GaAs MESFETs under compressive stress [7]. L_G dependence of MIT devices is consistent with piezoelectric effect.

which speeds up degradation [1,4]. Initially the [01$\bar{1}$] and [011] devices shift in opposite directions, consistent with the piezoelectric effect. Fig. 8 shows that the initial stage of degradation is also linear in $\sqrt{t}$. The rate of degradation decreases for increasing L_G. The $\sqrt{t}$ behavior of ΔV_T suggests that early degradation is rate limited by H diffusion through the gate. Fig. 9 shows that ΔV_T is also linearly dependent on $\sqrt{t}$ during the recovery process, again indicating a diffusive process.

The time dependent ΔV_T data reveals the presence of an additional mechanism that plays a role in the intrinsic device. Fig. 7 shows that after a certain annealing time in forming gas there is a sudden drop in V_T, followed by almost a complete saturation in its value. This drop in V_T even occurs for devices oriented along the [01$\bar{1}$] direction. The magnitude of the drop seems to be independent of L_G and orientation. The time required for this sudden drop appears to be proportional to L_G, as is evident in Fig. 10, which corresponds to a separate experiment on another die from the same wafer.

These results suggest the following explanation. When the gate metal is fully saturated with H, H diffuses down to the semiconductor substrate, producing a second V_T shift. This shift is independent of orientation or L_G. The time required for this to happen scales with L_G because the V_T measurements sample the electrostatics at the center of the gate. This L_G dependence suggests that bottleneck for early degradation is lateral diffusion of H through the gate.

We next examine the breakdown behavior. The increase in BV_{DG} can be explained with either an increase in ϕ_B, or a decrease in $n_{s(extr)}$ [5]. An increase in ϕ_B is inconsistent with the negative V_T shift observed for all devices. A reduction in $n_{s(extr)}$ could occur through donor passivation, changes in the extrinsic surface potential or induced piezoelectric charges in the extrinsic region. Piezoelectric charges are ruled out because there is no L_G or orientation dependence to ΔBV_{DG}. To address the issue of donor passivation we have annealed capped and uncapped Hall structures. There was no change in n_s for the capped device annealed in forming gas, but a 20%

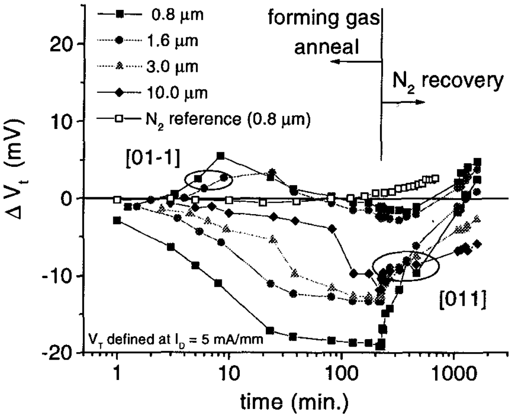

Figure 7: ΔV_T as a function of time for 3 hour anneal in forming gas at 200 ^{o}C, followed by 24 hour recovery anneal in N_2.

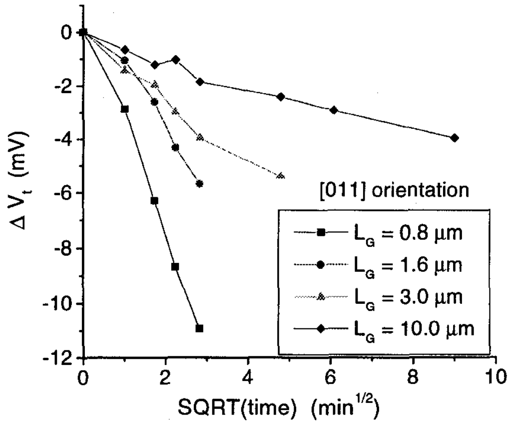

Figure 8: ΔV_T vs. $\sqrt{t}$ for [011] devices during early stages of degradation in forming gas anneal.

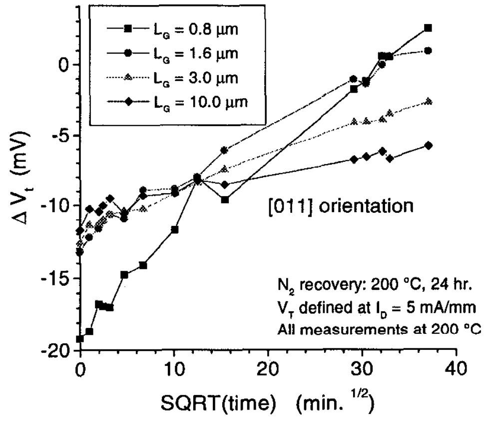

Figure 9: ΔV_T vs. $\sqrt{t}$ for [011] devices during N_2 recovery anneal. Linear behavior indicates a diffusive process.

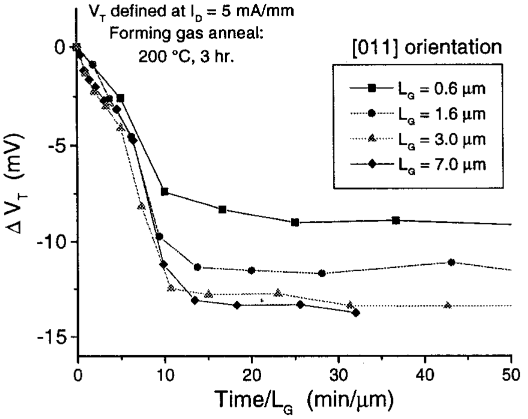

Figure 10: ΔV_T vs. time scaled by L_G. Gate length dependence of second V_T drop indicates the H is diffusing laterally through the gate.

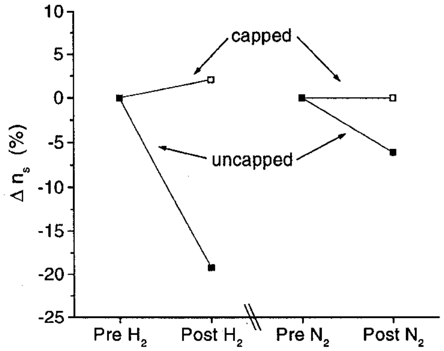

Figure 11: Measured n_s values after annealing in forming gas or N_2. H_2 degrades uncapped structures, but not capped structures. This rules out donor passivation as the cause of the reduction in $n_{s(extr)}$.

decrease in n_s for the uncapped device (Fig. 11). Since it is unlikely that the InGaAs cap is a significant barrier to hydrogen, donor passivation is ruled out. Thus, we attribute ΔBV_{DG} to a reduction in $n_{s(extr)}$ due to H_2 modifying the surface stoichiometry of the exposed InAlAs region, possibly producing a cation rich surface due to As desorption [11]. This effect would be not be recoverable in N_2.

Conclusions

In conclusion, we have found that H_2 exposure degrades InP HEMTs through two independent mechanisms, affecting the intrinsic and extrinsic regions, respectively. Examining the intrinsic region, we find that V_T shifts negative for InP HEMTs annealed in the presence of H_2, and largely recovers after further annealing in N_2. The ΔV_T data shows a clear orientation and inverse L_G dependence and is in part due to piezoelectric charges induced in the intrinsic device. The piezoelectric charge is attributed to stress in the gate, due to the formation of TiH. This has been confirmed through Auger measurements. In the extrinsic region, H_2 induces changes in the surface stoichiometry of the exposed InAlAs, reducing $n_{s(extr)}$. This is observed through measurement of BV_{DG}, which increases due to the reduction in $n_{s(extr)}$ after exposure to H_2, and does not recover. The physical understanding obtained in this work should be instrumental in identifying a permanent solution to this problem.

Acknowledgments

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