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 [5]. 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 50 °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.

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/Aln gates and ECR-enhanced, low-temperature Si$_3$N$_4$ 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 [011] 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 $\Delta V_T$ 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-annael and post-recovery. In a subset of devices, $\Delta V_T$ was monitored in situ at 200 °C as a function of time. We used $\Delta V_T$ to assess intrinsic device degradation and $\Delta BV_{DG}$ (off-state) to monitor degradation in the extrinsic device [5]. $V_T$ was measured with $V_{DS} = 0.1$ V to sample $n_{s(int)}$, near the center of the gate. $BV_{DC}$ 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. $\Delta V_T$ shows an inverse $L_Q$ behavior. Fig. 3 shows that there is also an orientation dependence in $\Delta V_T$, where the [011] devices shifted the most, followed by the [010], and then the [011]. 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.
\( \Delta V_T \) vs. \( L_G \) after annealing in forming gas, and after a subsequent anneal in \( N_2 \).

\( \Delta B_{DG} \) vs. \( L_G \) showing no \( L_G \) dependence. \( \Delta B_{DG} \) also showed no orientation dependence.

Figure 3: Orientation dependence of \( \Delta V_T \) as a function of gate length.

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

Discussion

The distinct behavior of \( V_T \) and \( B_{DG} \) 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 \( \Delta V_T \) are key signatures of the piezoelectric effect. Chaos 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 \( \gamma \)-phase TiH is possible in our experimental conditions. \( \gamma \)-phase TiH has a lattice volume 15% larger than Ti [10]. Forming gas anneals on unpassivated devices show nearly identical \( \Delta V_T \) behavior, confirming that the gate, and not the passivation layer, is the source of the stress.

The sign of \( \Delta V_T \) 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 \( \Delta V_T \) 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 \( \Delta V_T \), 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.
which speeds up degradation [1,4]. Initially the [011] 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 $\Delta V_T$ suggests that early degradation is rate limited by H diffusion through the gate. Fig. 9 shows that $\Delta V_T$ is also linearly dependent on $\sqrt{t}$ during the recovery process, again indicating a diffusive process.

The time dependent $\Delta V_T$ 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 [011] 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 bottlenecks 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 $\phi_B$, or a decrease in $n_{ext}$ [5]. An increase in $\phi_B$ is inconsistent with the negative $V_T$ shift observed for all devices. A reduction in $n_{ext}$ 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 $\Delta BV_{DG}$. To address the issue of donor passivation we have annealed capped and uncapped Hall structures. There was no change in $n_e$ for the capped device annealed in forming gas, but a 20%

Figure 6: Comparison of $\Delta V_T$ 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.

Figure 7: $\Delta V_T$ as a function of time for 3 hour anneal in forming gas at 200 °C, followed by 24 hour recovery anneal in N2.

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

Figure 9: $\Delta V_T$ vs. $\sqrt{t}$ for [011] devices during N2 recovery anneal. Linear behavior indicates a diffusive process.
the surface stoichiometry of the exposed InAlAs, reducing $n_{e(\text{extr})}$. This is observed through measurement of $B_{VDG}$, which increases due to the reduction in $n_{e(\text{extr})}$ 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.

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decrease in $n_e$ 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 $\Delta B_{VDG}$ to a reduction in $n_{e(\text{extr})}$ 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 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 $\Delta V_T$ 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 TH. This has been confirmed through Auger measurements. In the extrinsic region, H$_2$ induces changes in