STRESS-RELATED HYDROGEN DEGRADATION OF 0.1 µm InP HEMTs AND GaAs PHEMTs

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Abstract

Hydrogen degradation of III-V FETs is a serious reliability concern. Previous work has shown that threshold voltage shifts induced by H_2 exposure in 1 µm-channel InP HEMTs can be attributed to compressive stress in the gate due to the formation of TiH_x in Ti/Pt/Au gates. The compressive stress affects the device characteristics through the piezoelectric effect. The present work examined the H_2 sensitivity of 0.1 µm strained-channel InP HEMTs and GaAs PHEMTs. After exposure to H_2, the threshold voltage, V_T, of both types of devices shifted positive. *In situ* V_T measurements reveal that the V_T shifts show very distinctive time dependencies that are consistent with stress-related phenomena.

I. INTRODUCTION

Hydrogen degradation in III-V FETs is a well-documented and serious reliability concern [1-5]. Hydrogen exposure can occur when hydrogen out-gasses from packaging material and becomes trapped inside hermetically sealed packages. Over time, hydrogen leads to changes in the device characteristics, and can ultimately cause parametric module failures. To our knowledge, a device-level solution to this problem has not been reported for either InP or GaAs technologies.

Previous work has linked hydrogen degradation of InP HEMTs to the formation of TiH_x in Ti/Pt/Au gates [1]. Fig. 1 is a cartoon depicting the proposed degradation mechanism. According to this hypothesis, TiH_x formation produces compressive stress in the gate. This stress gives rise to a polarization volume charge distribution in the underlying semiconductor through the piezoelectric effect. The induced piezoelectric charge causes a negative V_T shift in [011] oriented devices [1]. That work was carried out in devices with lattice-matched channels and gate lengths in the 1 µm range.

In the present work, we report our finding that state-of-the-art InP HEMTs and GaAs PHEMTs with strained channels and deep submicron gate lengths behave in a very different way. After exposure to hydrogen, all these devices ([011]-orientation) exhibited a large *positive* V_T shift. Despite this puzzling result in the sign of ΔV_T, there is strong evidence that ΔV_T is related to stress nevertheless.

II. EXPERIMENTAL

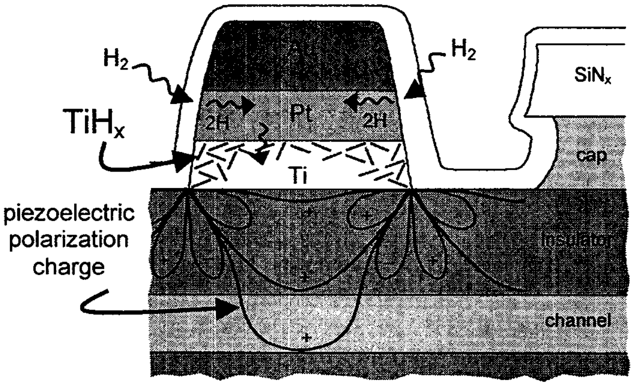

Fig. 1: Cartoon illustration of the proposed H_2 degradation mechanism of [1]. H_2 exposure leads to the formation of TiH_x, causing compressive stress in the gate. The induced piezoelectric polarization charge density in the semiconductor is indicated by the contours of constant charge for a [011]-oriented device.

This experiment examined 0.1 µm strained-channel InP HEMTs and GaAs PHEMTs with Ti/Pt/Au gates. The devices were fully passivated. All samples underwent a thermal burn-in at 250°C in N_2 for 1 hour, before being annealed at 200°C in a temperature-controlled wafer probe station. The probe station was equipped with a sealed chamber that allowed the introduction of either forming-gas (5% H_2 in N_2) or pure N_2. The devices were fully characterized at room temperature before and after the high-temperature anneals. In addition, V_T measurements were performed *in situ* at 200°C. Following H_2 exposure, the devices underwent a subsequent recovery anneal at 200°C in N_2 for up to 12 hours. The recovery anneal is designed to see if the hydrogen degradation can be annealed out with further thermal processing. Recovery behavior

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following H_2 degradation has frequently been reported in the literature [3, 4].

III. RESULTS

Examining first the InP HEMTs, we found that V_T shifted *positive* following exposure to forming-gas, as shown by the *in situ* ΔV_T data presented in Fig. 2. This is contrary to what is most frequently reported for InP HEMTs in the literature [1, 2]. The *in situ* V_T data taken during the N_2 recovery anneal in Fig. 2 shows that V_T only partially recovers. Fig. 2 also shows that some self-anneal takes place *during* hydrogen exposure for the InP HEMTs, consistent with reports in the literature [2, 3].

Fig. 3 shows the transconductance (g_m) characteristics of the InP HEMTs at room temperature before and after H_2 degradation. The V_T shift appears in the g_m characteristic as a lateral V_{GS} shift of g_m, with no reduction in its peak value. Unpassivated devices produced nearly identical results, showing that this shift cannot be attributed to the passivation layer.

After exposure to forming-gas, the V_T of GaAs PHEMTs also shifted positive, as shown in Fig. 4. This is consistent with GaAs PHEMT behavior reported in the literature [2-4]. Unlike the InP HEMTs, the ΔV_T of the GaAs PHEMTs did not exhibit any self-anneal effects during H_2 degradation. Fig. 4 also shows that the N_2 recovery anneal produced a slight recovery in V_T. The GaAs PHEMT g_m characteristics showed a V_{GS} shift corresponding to the ΔV_T similar to the InP HEMT behavior.

IV. DISCUSSION

The piezoelectric effect due to TiH_x formation postulated in [1] only explains a negative ΔV_T for devices oriented in the [011] direction. It cannot account for a positive ΔV_T at this time. However, a close examination of the *in situ* ΔV_T measurements revealed distinctive time dependencies that are characteristic of stress-related phenomena nevertheless.

Fig. 5 shows the *in situ* ΔV_T data re-plotted on a $t^{5/2}$ scale, revealing a clear linear dependence during hydrogen degradation for both the InP HEMTs and GaAs PHEMTs. This unusual time dependence has been associated with a volumetric increase due to hydride precipitation in the Zr-H system [6]. The Zr-H system is very similar to the Ti-H system. In this model, the hydride precipitates have a platelet geometry and nucleate on grain boundaries at a constant rate [6]. The nucleation is driven by hydrogen diffusion along grain boundaries, exhibiting a $t^{1/2}$ dependence. For 2D platelets that have negligible interaction during hydride growth, the platelet volume increases at a rate $\propto t$. The growth-rate of the hydrided fraction of material is equal to the product of these two processes, giving a $t^{3/2}$ dependence. The fraction of hydrided material is the time integral of this, and therefore has a $t^{5/2}$ dependence. The stress in the material is expected to be proportional to the fraction of hydrided material [6].

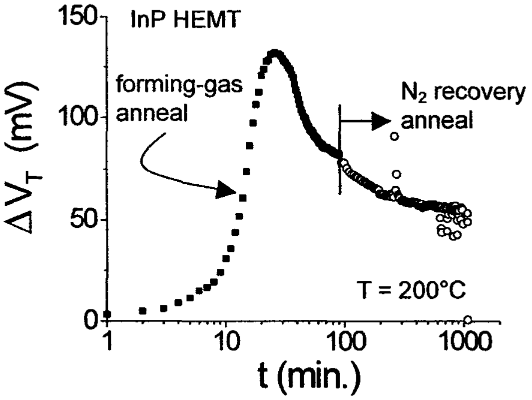

Fig. 2: ΔV_T vs. *t* for InP HEMTs during forming-gas anneal at 200°C for 2 hrs. (squares) and during a subsequent N_2 recovery anneal at 200°C for 15 hrs. (circles). Measurements taken *in situ* at 200°C.

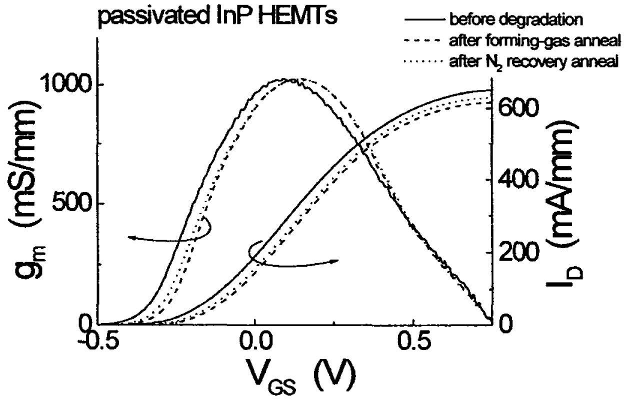

Fig. 3: g_m and I_D vs. V_{GS} for InP HEMTs before and after forming-gas anneal at 200°C for 2 hrs., and after a subsequent N_2 recovery anneal at 200°C for 15 hrs. Measurements taken at 25°C.

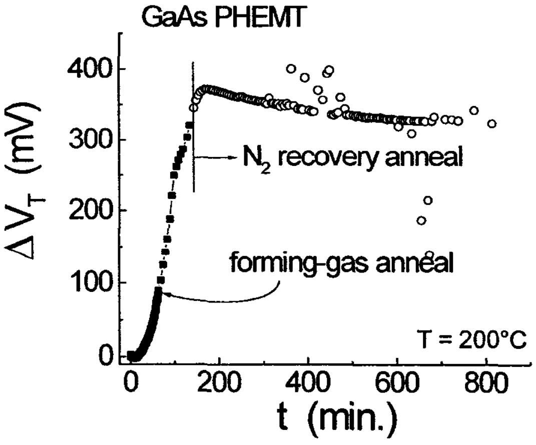

Fig. 4: ΔV_T vs. *t* for GaAs PHEMTs during forming-gas anneal at 200°C for 2 hrs. (squares) and during a subsequent N_2 recovery anneal at 200°C for 15 hrs. (circles). Measurements taken *in situ* at 200°C.

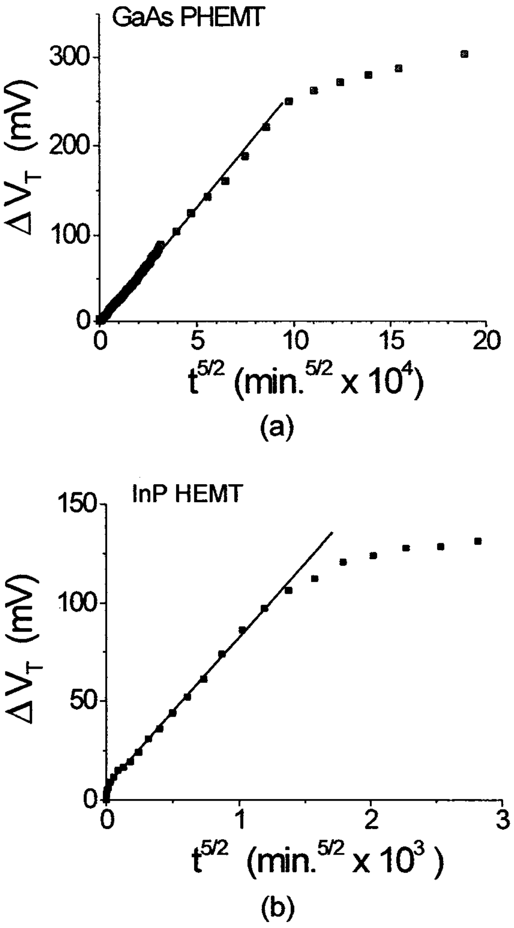

Fig. 5: ΔV_T data from (a) GaAs PHEMTs and (b) InP HEMTs, re-plotted on a $t^{5/2}$ scale. The linear relationship is evidence that ΔV_T is related to stress.

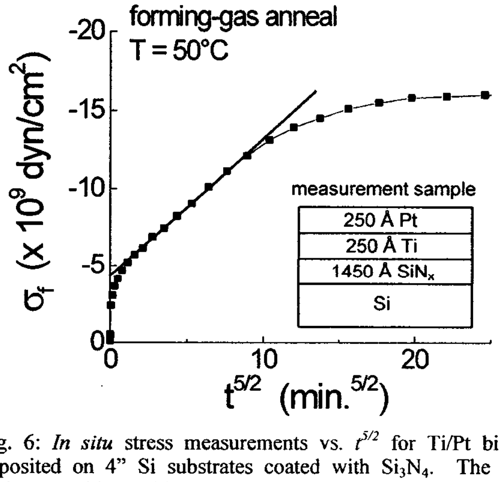

Fig. 6: *In situ* stress measurements vs. $t^{5/2}$ for Ti/Pt bilayers deposited on 4" Si substrates coated with Si_3N_4. The linear region provides evidence that stress in the gate due to TiH_x formation is responsible for the ΔV_T behavior observed on the transistors.

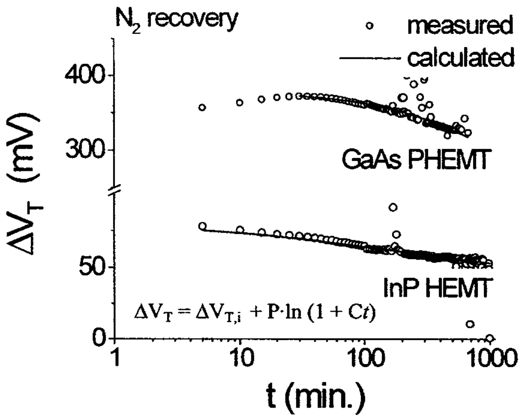

Fig. 7: Calculated and measured ΔV_T vs. $t^{5/2}$ for InP HEMTs and GaAs PHEMTs during N_2 recovery anneal. The functional agreement between the calculated and measured values is evidence that the ΔV_T recovery is related to the relaxation of stress in the gate through dislocation glide.

To examine more critically this behavior in the Ti-H system, we have conducted *in situ* stress measurements on Ti/Pt bilayers. The test structures were 250 Å Pt/ 250 Å Ti layers deposited on 4" Si wafers which were coated with 1450 Å of LPCVD Si_3N_4. The stress was monitored through radius-of-curvature measurements using a Tencor FLX-2320. The measurement system has a heated chuck and gas inlets which allow the introduction of N_2 or forming-gas. The wafer stress was measured *in situ* as a function of time. Fig. 6 shows the results of this experiment. The volume increase associated with the formation of TiH_x causes compressive stress in the Ti/Pt bilayers. Consistent with the transistor *in situ* ΔV_T measurements, we observed a well-defined region where the stress is proportional to $t^{5/2}$ in the Ti/Pt bilayers as well. These results provide strong evidence that ΔV_T is related to stress.

Fig. 7 shows the *in situ* ΔV_T data taken during the N_2 recovery anneal re-plotted on a *log t* scale, revealing a nearly linear dependence. This time dependence has been associated with stress relaxation due to the movement of dislocations, often called dislocation glide [7, 8]. In this theory, the thermal movement of dislocations is enhanced by stress in the material, resulting in a characteristic equation given by $\sigma = \sigma_i - P\ln(1 + Ct)$, where σ_i is the initial film stress [7, 8]. This functional dependence provides an excellent fit to the ΔV_T data.

This stress-relaxation phenomenon was also observed on the same Ti/Pt bilayers through *in situ* stress measurements. The Ti/Pt test films were exposed to H_2 through a forming-gas anneal. The forming-gas was then turned off, and N_2 was pumped into the stress-measurement system. During the subsequent N_2 recovery anneal, the stress in the film relaxed at a rate proportional to *log t*, as shown in Fig. 8. This relaxation behavior is therefore also consistent with a gate-stress origin to ΔV_T. We speculate that the self-annealing that is observed

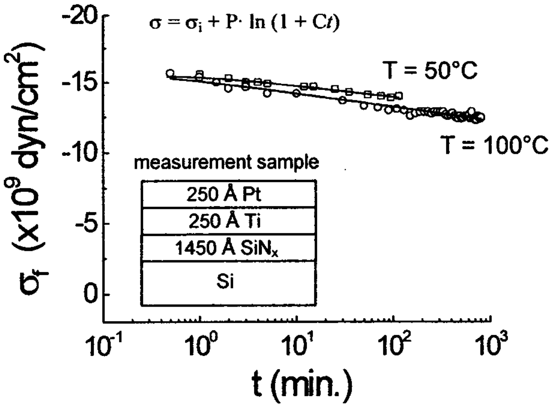

Fig. 8: *In situ* stress measurements as a function of *log t* for hydrogenated Ti/Pt bilayers films during a subsequent N_2 recovery anneal. The functional agreement between measurements and calculations indicates that dislocation glide is responsible for stress relaxation in Ti/Pt films.

in InP HEMTs during H_2 exposure (Fig. 2) might well be due to stress relaxation prevailing over stress build-up due to hydride formation.

A number of complications arise for 0.1 μm gate-length devices that may account for the *positive* ΔV_T rather than a negative ΔV_T as predicted in [1]. The simplistic stress model used in [1] is no longer valid for gate lengths less than about 6 times the film thickness of the stressed film, in this case the gate metalization. A finite-element simulation is required to accurately calculate the piezoelectric polarization charge distribution in the semiconductor under short-channel conditions. Additional complications are possible for strained-channel devices. In strained-channel heterostructures, if the coherent strain is sufficiently high the material will no longer be in a linear stress-strain regime. In this case, the stress induced in the channel and insulator regions may be quite different. Further studies are underway to determine the origin of the positive V_T shift.

V. CONCLUSION

In conclusion, previous work has shown that hydrogen degradation of InP HEMTs is related to compressive stress in Ti/Pt/Au gates due to the formation of TiH_x. In the present work, we have found that exposure to H_2 caused a positive V_T shift in 0.1 μm InP HEMTs and GaAs PHEMTs. *In situ* ΔV_T measurements revealed distinctive time dependencies that are characteristic of stress-related phenomena. These time dependencies have also been observed on hydrogenated Ti/Pt test layers, confirming that they too are associated with the Ti/Pt/Au gate. This understanding should be instrumental to identifying a device-level solution to this problem.

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