Hydrogen-Induced Piezoelectric Effects in InP HEMT's

Roxann R. Blanchard, Jesús A. del Alamo, Stephen B. Adams, P. C. Chao, and Albert Cornet

***Abstract*—In this letter, we have investigated hydrogen degradation of InP HEMT's with Ti/Pt/Au gates. We have found that V_T shifts negative after exposure to hydrogen, and exhibits an L_G and orientation dependence. We postulate that ΔV_T is at least in part due to the piezoelectric effect. Hydrogen exposure leads to the formation of TiH_x, producing compressive stress in the gate. This stress induces a piezoelectric charge distribution in the semiconductor that shifts the threshold voltage. We have independently confirmed TiH_x formation under our experimental conditions through Auger measurements. Separate radius-of-curvature measurements have also independently confirmed that Ti/Pt films become compressively stressed relative to their initial state after H_2 exposure.**

***Index Terms*— Hydrogen, InP HEMT's, piezoelectric effect, stress, Ti/Pt/Au gates.**

I. INTRODUCTION

HYDROGEN degradation in III–V FET's is a serious and well documented reliability concern [1]–[4]. Exposure occurs when hydrogen outgasses from packaging material and gets trapped inside hermetically sealed packages. Over time, hydrogen causes changes in device characteristics which can ultimately lead to parametric module failures. Compared with the more extensive studies of H_2 degradation of GaAs MESFET's and PHEMT's, only limited data on the H_2 sensitivity of InP HEMT's is available. V_T is generally reported to decrease in InP HEMT's, although exposure times for published data are under 20 min [2]. To our knowledge, a device-level solution to this problem has not been reported for either InP or GaAs technologies.

While the detailed mechanism by which H_2 affects the operation of III–V FET's is not understood, previous researchers have traced the degradation to the presence of Pt in the gate stack [1]. Pt is known to be a catalyst for H_2, breaking it down into 2H, which then diffuses through the gate. However, Chao [4] showed that degradation also occurred in GaAs PHEMT's fabricated with Ti-only gates. This led them to speculate on the formation of TiH_x and a subsequent change in the Schottky barrier height of the gate.

Manuscript received December 24, 1998; revised April 5, 1999. This work was supported in part by Sanders Lockheed-Martin. This work made use of MRSEC Shared Facilities supported by the National Science Foundation under Award Number DMR-9400334.

R. R. Blanchard and J. A. del Alamo are with the Massachusetts Institute of Technology, Cambridge, MA 02139 USA.

S. B. Adams and P. C. Chao are with Sanders Lockheed Martin, Nashua, NH 03060 USA.

A. Cornet is with the Universitat de Barcelona, Barcelona, Spain.

Publisher Item Identifier S 0741-3106(99)06461-7.

In this letter, we present evidence that the formation of TiH_x leads to the introduction of stress in the gate and in the underlying semiconductor heterostructure. Since all compound semiconductors are piezoelectric, this stress induces a volume charge distribution in the heterostructure [5]. This affects the threshold voltage, and in turn the device characteristics. It is likely that the mechanism proposed here contributes to the hydrogen sensitivity of GaAs MESFET's and PHEMT's as well.

II. EXPERIMENTAL

The InP HEMT's used for this study were fabricated at MIT. The device heterostructure consists of semi-insulating InP substrate, 2500 Å $In_{0.52}Al_{0.48}As$, bottom δ-doping, 50 Å $In_{0.52}Al_{0.48}As$ spacer, 200 Å $In_{0.53}Ga_{0.47}As$ channel, 30 Å $In_{0.52}Al_{0.48}As$ spacer, top δ-doping, 270 Å $In_{0.52}Al_{0.48}As$ insulator, and a 70 Å undoped $In_{0.53}Ga_{0.47}As$ cap. The fabrication process features a selective cap recess, sidewall recess isolation, dielectric-assisted lift-off, Ni/AuGe/Ni alloyed contacts and ECR-enhanced, low-temperature Si_3N_4 passivation. The gate metal is 250 Å Ti/250 Å Pt/3000 Å Au, with gate lengths of 0.6–10 μm. On a (100) substrate, devices with gates oriented along the [011], [010], and [01$\bar{1}$] direction were characterized.

Hydrogen exposure and characterization 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 at 230 °C in N_2 until no further change in threshold voltage, ΔV_T, was measured. The devices were then annealed unbiased at 200 °C for 3 h in forming-gas. For reference, selected burned-in devices were annealed in N_2 under identical conditions. A detailed room-temperature characterization was performed preanneal and post-anneal. To monitor degradation in the intrinsic portion of the device, V_T was measured with $V_{DS} = 0.1$ V in order to sample $n_{s(intr)}$ near the center of the gate.

III. RESULTS AND DISCUSSION

Under forming-gas, we found that V_T shifted negative for all devices, as shown in Fig. 1. This is consistent with previous studies on 0.1-μm InP HEMT's [2]. While the measured V_T shifts are small, they are statistically significant when compared to the N_2 control. Fig. 1 also shows that ΔV_T exhibits a distinct gate length dependence.

Fig. 2 shows the orientation dependence of ΔV_T, plotted as a function of L_G. Devices with gates orientated along the

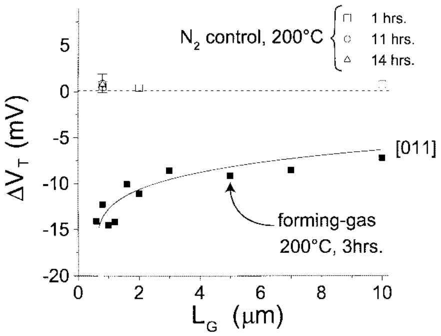

Fig. 1. ΔV_T verses L_G after annealing in forming-gas at 200 °C for 3 h. Open symbols are control samples annealed in N_2 at 200 °C. Error bars on control samples annealed for longer times indicate standard deviation in measurement over time. V_T defined at $I_D = 4$ mA/mm. Measurements at room temperature.

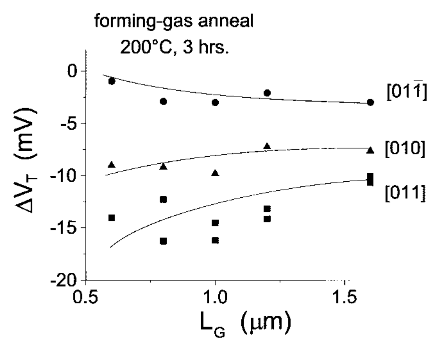

Fig. 2. Orientation dependence of ΔV_T as a function of gate length, showing greater negative ΔV_T for [011] devices. Forming-gas anneal for 3 h at 200 °C. Measurements at room temperature.

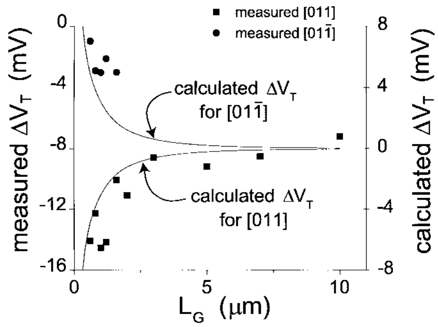

Fig. 3. Comparison of measured ΔV_T versus L_G data (left axis) with the ΔV_T determined from calculations (right axis). The calculated ΔV_T is due to piezoelectric charges induced by a compressive stress of 1.5×10^9 dyn/cm^2 in the gate. In this calculation, the one-dimensional piezoelectric charge distribution in the semiconductor at the center of the gate is calculated, following the method of [9]. The L_G and orientation dependencies are consistent with the piezoelectric effect. Devices annealed in forming-gas for 3 h at 200 °C. Measurements at room temperature.

[011] direction shifted more negative than those with the gate along the [01$\bar{1}$] direction.

The L_G and orientation dependencies of ΔV_T are key signatures of the piezoelectric effect. Similar dependencies reported for GaAs MESFET's with stressed dielectric overlayers have also been attributed to the piezoelectric effect [6], [7]. Hydrogen-induced degradation in GaAs PHEMT's with Ti-only gates lead Chao [4] to speculate on the formation of TiH_x and a change in the Schottky barrier height. This explanation should not result in an L_G or orientation dependence. Instead, since all phases of TiH_x have a larger lattice constant than Ti [8], the formation of TiH_x produces compressive stress in the gate. This stress affects V_T by inducing a piezoelectric charge distribution in the semiconductor [5]. In order to rule out the Si_3N_4 passivating overlayer as a source of stress, we also performed forming-gas anneals on unpassivated devices. The unpassivated devices showed nearly identical ΔV_T behavior to passivated devices, showing that the passivation is not a source of stress.

To examine this hypothesis further, in Fig. 3 we compare the measured ΔV_T data with the predicted ΔV_T from gate stress of -1.5×10^9 dyn/cm^2 (compressive), following the method of [9]. The L_G and orientation dependencies of ΔV_T agree well with calculations once we account for a rigid 8 mV offset. This additional ΔV_T is affected by annealing under bias, and may arise from H^+ penetration into the semiconductor. While this rigid shift is currently under study, we note that it is limited to 8 mV and does not exhibit any L_G or orientation dependence. Therefore, unlike the piezoelectric component of ΔV_T which increases significantly for short channel devices, we do not expect this second mechanism to contribute substantially to degradation in state-of-the-art 0.1-μm HEMT's.

To confirm the formation of titanium hydride, we have performed Auger analysis on test samples of 250 Å Ti/250 Å Pt deposited on Si wafers coated with LPCVD Si_3N_4. These samples were annealed in either forming-gas or pure N_2 at 200 °C for 1 h. The sample annealed in forming-gas showed a 1 eV shift in the low-energy (26 eV) peak of Ti, and the emergence of a second peak at 5 eV below the main peak. These changes are the characteristic signature of TiH_x [10]. In conditions similar to ours, with a low atomic percent of hydrogen (<10%), the formation of hydride precipitates with an FCT structure has been reported in monocrystalline titanium [8]. These precipitates have a 15% volume increase with respect to the Ti matrix. In our polycrystalline titanium, the precipitates are expected to form at grain boundaries, and can be affected by localized stress and dislocations [8]. Assuming a 15% $\Delta V/V$ for the TiH_x precipitates, with an overall H_2 concentration of 5%, the predicted net volume expansion is about 0.7%. A simple calculation of the film stress due to this net volume expansion predicts a film stress of about 2.5×10^9 dyne/cm^2. The order of magnitude of the stress predicted by this simple model is the same as the stress used in our calculations of ΔV_T.

In further support of the piezoelectric hypothesis, radius-of-curvature measurements have also independently confirmed that Ti/Pt films undergo a volume expansion after H_2 exposure. The test samples were identical to those used in the Auger measurements. The measurement unit has a heated chuck and gas inlets for introducing either forming-gas or pure N_2. After reaching thermal equilibrium, the radius-of-curvature was measured *in situ* as a function of time. The results of this experiment are shown in Fig. 4. The Ti/Pt films annealed in forming-gas exhibits a volume expansion, as indicated by the increase in wafer bowing, after only a few seconds of exposure. This volume expansion represents compressive

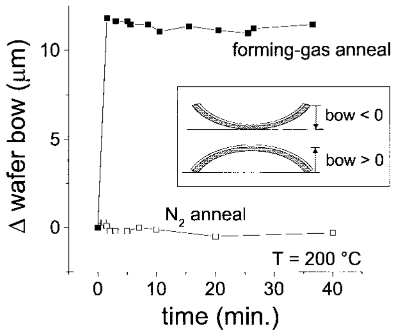

Fig. 4. Change in wafer bow obtained from radius-of-curvature measurements as a function of time for Ti/Pt films deposited on 4-in silicon wafers coated with Si_3N_4. The increase in curvature indicates that the film undergoes volume expansion due to H_2 exposure, consistent with compressive stress relative to its initial state. Anneals performed at 200 °C. Measurements taken *in situ* at 200 °C.

stress in the film, relative to its initial state. In comparison, the wafer curvature of the N_2 control sample remains relatively unchanged throughout the anneal, indicating no change in the stress state of the Ti/Pt film.

IV. Conclusions

In conclusion, we find that after exposure to H_2, V_T shifts negative for InP HEMT's with Ti/Pt/Au gates. The ΔV_T exhibits an L_G and orientation dependence, and can be attributed in part to the piezoelectric effect. Stress develops in the gate due to the formation of TiH_x after exposure to H_2. This stress creates a piezoelectric charge distribution in the semiconductor, which changes the threshold voltage. We have independently confirmed through Auger measurements that TiH_x is formed under our experimental conditions. In addition, radius-of-curvature measurements have independently confirmed that Ti/Pt films undergo volume expansion after exposure to H_2. The physical understanding obtained in this work should be instrumental in identifying a permanent solution to this problem.

Acknowledgment

The device fabrication was carried out at the Microsystems Technology Laboratory of Massachussetts Institute of Technology.

References

[1] W. O. Camp, Jr., R. Lasater, V. Genova, and R. Hume, "Hydrogen effects on reliability of GaAs MMIC's," in *IEEE GaAs IC Symp.*, 1989, p. 203.

[2] P. C. Chao, M. Y. Kao, K. Nordheden, and A. W. Swanson, "HEMT degradation in hydrogen gas," *IEEE Electron Device Lett.*, vol. 15, p. 151, May 1994.

[3] W. W. Hu, E. P. Parks, T. H. Yu, P. C. Chao, and A. W. Swanson, "Reliability of GaAs PHEMT under hydrogen containing atmosphere," in *IEEE GaAa IC Symp.*, 1994, p. 247.

[4] P. C. Chao, W. Hu, H. DeOrio, A. W. Swanson, W. Hoffmann, and W. Taft, "Ti-gate metal induced PHEMT degradation in hydrogen," *IEEE Electron Device Lett.*, vol. 18, p. 441, Sept. 1997.

[5] S. Adams, 1998, private communication.

[6] C. P. Lee, R. Zucca, and B. M. Welch, "Orientation effect on planar GaAs Schottky barrier field effect transistors," *Appl. Phys. Lett.*, vol. 37, no. 3, p. 311, 1980.

[7] N. Yokoyama, H. Onodera, T. Ohnichi, and A. Shibatomi, "Orientation effect of self-aligned source/drain planar GaAs Schottky barrier field-effect transistors," *Appl. Phys. Lett.*, vol. 42, no. 3, p. 270, 1983.

[8] H. Numakura and M. Kiowa, "Hydride precipitation in titanium," *Acta Metall.*, vol. 32, no. 10, p. 1799, 1984.

[9] P. M. Asbeck, C.-P. Lee, and M.-C. F. Chang, "Piezoelectric effects in GaAs FET's and their role in orientations-dependent device characteristics," *IEEE Trans. Electron Devices*, vol. ED-31, p. 1377, Oct. 1984.

[10] P. Bracconi and R. Lässer, "Investigation of titanium and titanium hydride by AES and EELS," *Appl. Surf. Sci.*, vol. 28, p. 204, 1987.