Hydrogen sensitivity of InP HEMTs with a thick Ti-layer in the Ti/Pt/Au gate stack

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We have investigated the hydrogen sensitivity of InP HEMTs with a gate stack containing a thick Ti-layer (order of 1000 Å). We have found that the hydrogen-induced piezoelectric effect in these devices is an order of magnitude smaller than conventional Ti/Pt/Au-gate HEMTs with a thin Ti layer (order of 250 Å). This markedly improved reliability can be explained through the diffusion mechanism of H in Ti which limits hydrogenation of the Ti layer to a thin sheet at the top. Using Auger Electron Spectroscopy, we have confirmed that under the studied conditions, TiH_x is only formed in the top 250 Å of the Ti-layer. In some devices located in the periphery of the wafer, we have observed a second hydrogen degradation mechanism that induces a large positive ΔV_T. This appears to be related to an improperly fabricated gate recess. The use of a thick Ti layer in the gate stack allows for a simple and effective mitigation of the H-induced piezoelectric effect in InP and other III-V HEMTs.

I. Introduction

The goal of this research is to investigate device designs that mitigate or eliminate the H-sensitivity of InAlAs/InGaAs HEMTs. H degradation is a serious reliability concern in III-V HEMTs [1]. H is known to alter the electrical characteristics of the devices ultimately leading to parametric failure. One of the paths for H to affect III-V HEMTs is the formation of TiH_x in the Ti/Pt/Au gate stack [2]. This creates tensile stress in the heterostructure underneath which induces piezoelectric charge under the gate causing a threshold voltage shift. Fig. 1 shows previously reported ΔV_T in various InP HEMTs caused by a bake in a forming gas atmosphere.

This model of H degradation implies that devices with a thick Ti layer should exhibit a larger V_T shift [3]. To verify this, we have carried out in this work a study of the H sensitivity of InP HEMTs with a thick Ti layer in the gate stack. Surprisingly, we experimentally found that the piezoelectric H-sensitivity of these devices was very low. In fact, it was nearly as good as that of devices with WSiN in the gate stack, which are the most H insensitive devices to date [4]. This is an important finding because the H sensitivity of Ti/Pt/Au-gate HEMTs can be drastically improved without requiring drastic process changes. Our work has also identified a second H-induced degradation mechanism, likely related to an undesirable processing-issue.

II. Experimental

The investigated InP HEMTs (Fig. 2) feature a Ti/Pt/Au gate stack with a 1000 Å thick Ti layer with gate lengths between 30 nm and 1 μm. The devices have been originally designed and optimized for the $[01\bar{1}]$ gate orientation and for a WSiN/Ti/Pt/Au gate.

We have followed a methodology similar to that of [2] consisting of three phases. Electrical device characterization was carried out at room temperature before and after every phase. The characterization suite was developed to minimally alter the device behavior. First, the devices were baked in N_2 at 195°C for over 100 hours to saturate all thermally induced effects. In a second phase, the thermal stability was evaluated by baking the devices again at 195°C for 2 h under N_2. Finally, the devices are baked at 195°C for 2h in forming gas containing 5% N_2. This allows us to compare the effects of a 2-hour thermal bake in N_2 and in forming gas and thus estimate the effects of H in a single device.

III. Electrical Results

Fig. 3 shows ΔV_T as a function of the gate length after the 2h N_2 and H_2 treatments. After 2h N_2 annealing, V_T typically changes less than 10 mV. In contrast, under forming gas, V_T is seen to change over a wide range. A cluster of devices exhibits very small and mostly negative V_T changes, while in others, V_T change by as much as 100 mV.

In order to bring some understanding to this picture, we have examined many other device figures of merit, such as R_D, R_S and I_G. In general, we have seen that there are two distinctive device populations. One of these is characterized by mostly small and negative ΔV_T, very small shifts in the parasitic resistances and the forward-biased gate current after exposure to forming gas. In the other population, the H-induced ΔV_T is positive and widely scattered. In these, the forward-biased gate current increases significantly and the parasitic resistances decrease. To quantify this, we have translated the increase in forward I_G into a shift of the Schottky barrier height of the gate, $\Delta\phi_B$, by examining the forward voltage that

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results in I_G= 1 mA/mm. At this current level, the forward branch of I_G follows an ideal exponential behavior. This shift in Schottky barrier height, $\Delta\phi_B$, during H-exposure is plotted in Fig. 4 as a function of ΔV_T for all devices. One cluster of devices shows both small shifts in V_T and in ϕ_B, while the rest of the devices show a wide scatter in $\Delta\phi_B$ and ΔV_T.

We also examined the relative location of these transistors on the wafer. We found that the two populations had different distributions. The devices showing significant H-induced $\Delta\phi_B$ are mostly located on the edge of the wafer, while the devices showing very small $\Delta\phi_B$ were mostly found in the center.

These results suggest that there are two different mechanisms at play here. In order to separate them, we bin the transistors in two groups according to the shift in ϕ_B that takes place during H-exposure. This selection criteria should separate devices for which ΔV_T takes place through the piezoelectric effect from those in which V_T shifts by a different mechanism. A binning criteria of $\Delta\phi_B$=10 meV was selected.

Fig. 5 shows the ΔV_T distribution of devices that exhibit a hydrogen-induced $\Delta\phi_B$ that is less than 10 meV (these are all located towards the center of the wafer). With a small number of exceptions, devices with short L_g in this population show small negative ΔV_T of the order of 20 mV, while long devices also show a small positive ΔV_T of the order of 30 mV. These are about an order of magnitude smaller than that observed in devices with Ti/Pt/Au gates in the $L_g\approx0.1$ μm range under similar H-exposure conditions [1] and comparable to the most hydrogen insensitive devices reported to date that feature a WSiN gate [4]. Other changes in the device characteristics are consistent with those previously attributed to the H-induced piezoelectric effect, such as a constant Schottky barrier height and small increases in the parasitic resistances [1,2]. The medians of ΔV_T at a set gate length range between –9 mV and +5 mV (the average is not a good statistical figure of merit for a distribution such as this one that is spread around a value close to zero).

The Schottky-barrier shift decreases for higher L_g, so this shift will not be as successful in separating the two families of devices for longer devices.

The second population of devices, mainly located towards the edge of the wafer, shows a widely scattered distribution in ΔV_T and $\Delta\phi_B$ and a reduction in the parasitic resistances. These changes in the device characteristics are similar to those occurring during the prebake in N_2 and are not consistent with the H-induced piezoelectric effect. All indications are that this type of degradation is related to processing variations during the fabrication of the devices. If the InP etch stop layer is not completely etched and comes in contact with the Ti layer in the gate stack, during annealing, the Ti will sink into it changing the electrical characteristics of the metal/semiconductor interface [5]. Our prebake sequence should completely exhaust this effect, however, it is possible that the presence of hydrogen enhances this effect. Since this mechanism is not related to the piezoelectric effect or any other previously reported H-induced degradation mechanism, but most likely to a processing issue, it should not affect the H-sensitivity of properly fabricated and designed InP HEMTs with Ti/Pt/Au gates.

IV. AES observations

The small V_T shift due to the H-induced piezoelectric effect that we have observed is inconsistent with a homogenous expanding Ti layer model. For this orientation, this would result in a very large and negative ΔV_T [3]. However, these results could be explained if Ti hydrogenation only occurs in a shallow region at the top of the Ti layer. If this was the case, the remaining Ti will absorb part of the mechanical stress and reduce the overall H sensitivity of the device. This is indeed very likely as TiH_x is a known barrier for H-diffusion [6]. This is because the diffusion mechanism of H in Ti occurs via the same tetrahedral sites that H occupies in TiH_x [7]. The Pt layer in the gate stack is a catalyst for breaking up molecular H_2 in atomic H. So, diffusion of the atomic hydrogen into the Ti-layer mostly initiates from the Ti/Pt interface. This atomic H reacts with the Ti to form TiH_x which blocks further diffusion of atomic H through the Ti.

In order to verify this hypothesis, we have experimentally evaluated the composition of the Ti layer as a function of depth using Auger Electron Spectroscopy (AES) [8]. The Auger spectra were collected using a primary beam energy of 2 keV with a modulation voltage of 2 V. The measurement system uses a rastered beam. The composition profiles were obtained using Ar ion sputtering. Test samples consisting of a Si substrate covered with Si_3N_4, 1000 Å of Ti and 250 Å of Pt were exposed to forming gas at 200 °C for 2 h. We investigated the energy spectrum around the low energy Ti-peak. The characteristic AES signature of TiH_x is a shift of +1 eV in the low energy Ti peak and the emergence of a hydride peak 5 eV below it [9].

AES spectra of the low energy Ti peak at different depths are shown in Fig. 6. The upper layers are clearly seen to contain TiH_x but at 300 Å in depth, the Ti is essentially unreacted. An estimate for the relative TiH_x content as a function of depth is shown in Fig. 7. This estimate is the height of the low-energy Ti-peak, normalized to the value at the Ti/Pt interface. Only the upper 200 Å of the Ti are seen to contain TiH_x. This is consistent with the small H sensitivity of HEMTs with a thick Ti layer in the gate stack.

V. Simulations

In order to verify this explanation, we carried out device simulations using the techniques described in [3] which involve 2D finite element simulations using ABAQUS and 1D electrostatics calculations using MATLAB. We modeled a "reference" device with a 1000 Å Ti/ 250 Å Pt/ 3000 Å Au gate stack and a layer structure consisting of 2000 Å InAlAs/150 Å InGaAs/100 Å InAlAs (from bottom to top) [4]. The results of these simulations are shown in Fig. 8 for a [01$\bar{1}$] gate orientation.

Three different scenarios were simulated. In the first scenario the complete Ti gate reacts with H and expands. In the second and third case, the top 250 Å and 100 Å of the Ti layer respectively form TiH_x and expand. Fig. 8 shows the calculated ΔV_T as a function of the gate length for these three different situations. If only the top 250 Å of Ti layer expands as opposed to the entire layer, ΔV_T decreases by an order of magnitude. When the thickness of the expanding layer further shrinks to 100 Å, ΔV_T halves again. This is consistent with the experimental observations of Fig. 3. As the expanding layer thins and is further removed from the semiconductor, the mechanical stress in the semiconductor decreases, which decreases the piezoelectric charge and the hydrogen-induced ΔV_T.

VI. Summary

We found that a thick Ti-layer in the Ti/Pt/Au gate of an InP HEMT reduces the sensitivity to the H-induced piezolectric effect by an order of magnitude. This can be explained through the diffusion mechanism of H in Ti which limits hydrogenation of the Ti layer to a thin sheet at the top. AES showed us that TiH_x is only formed in the top 250 Å of the Ti-layer. We have observed a second hydrogen mechanism that induces larger positive ΔV_T but is likely related to an anomalous processing issue. Assuming that this can be resolved, these results represent good news for InP HEMTs, as the H-induced piezoelectric effect in these devices can still be mitigated by simply using a Ti/Pt/Au gate stack with a thick Ti layer. This approach, compared to using a WSiN-layer to separate the thin Ti-layer from the semiconductor [4], has advantages in simplicity.

Acknowledgements

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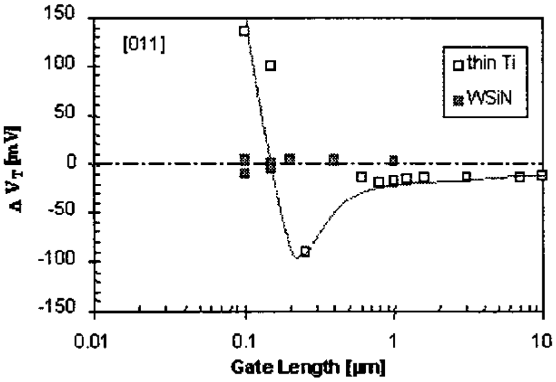

Fig. 1: Reported H-induced threshold voltage shifts with conventional thin Ti-layers in the Ti/Pt/Au gate stack [10-14] and with WSiN/Ti/Pt/Au gate stacks [4]. The devices have a [011] gate orientation.

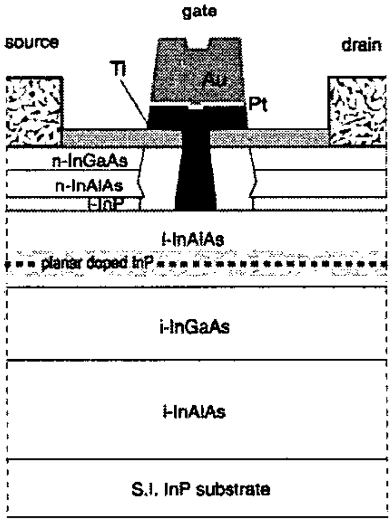

Fig. 2: InP HEMTs studied in this work. The intrinsic heterostructure consists of from bottom to top: 2000 Å InAlAs/ 150 Å InGaAs/ 90 Å InAlAs. The gate consists of 1000 Å Ti topped with Pt and Au layers.

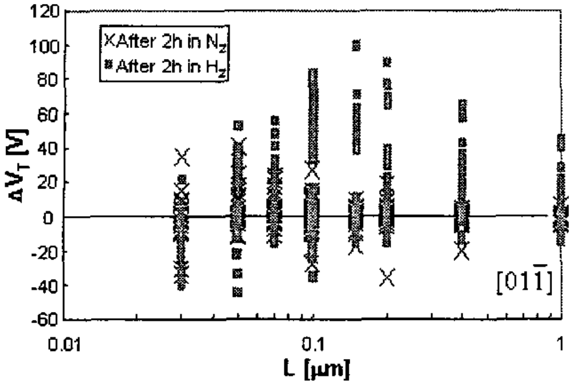

Fig. 3: Threshold voltage shifts caused by a bake at 195°C in N_2 and in forming gas (5% H_2).

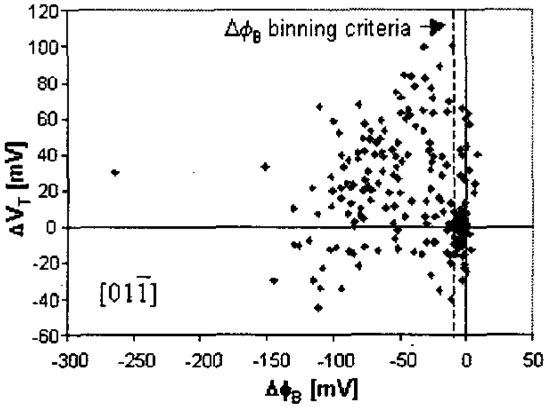

Fig. 4: Shift in V_T in function of the change of the Schottky-barrier height, $\Delta\phi_B$, during a 2h exposure to forming gas at 195°C. The binning criteria of $\Delta\phi_B$= 10 meV has been marked.

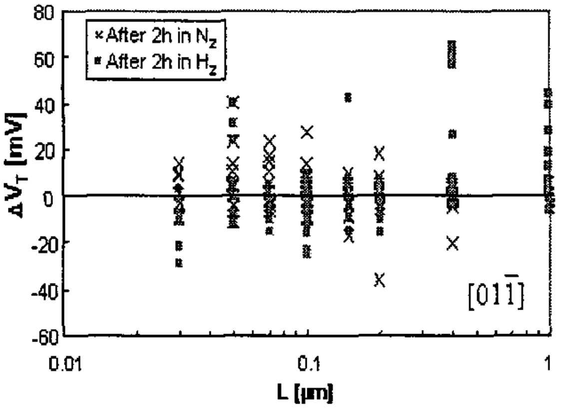

Fig. 5: Threshold voltage shifts caused by a bake at 195°C in N_2 and in forming gas for devices that showed a $\Delta\phi_B$ less than 10 meV during the bake in forming gas.

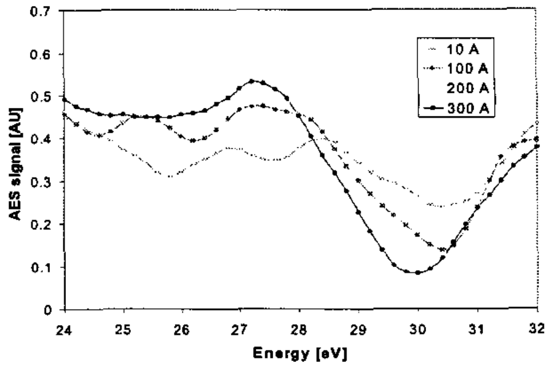

Fig. 6 Auger spectra of low-energy Ti peak at different depths of a Ti/Pt bilayer after 2h exposure to forming gas at 200 °C. Sample structure is shown in inset of Fig. 7.

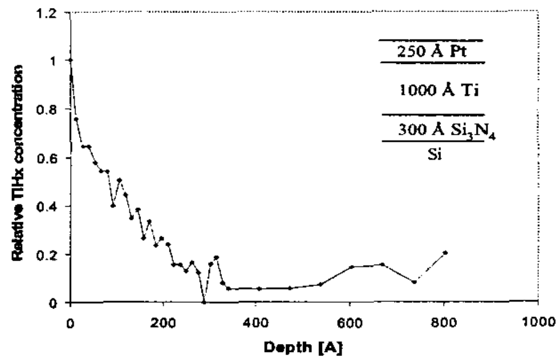

Fig. 7 Depth profile of TiHx concentration, normalized to its value at the Pt/Ti interface, as measured by Auger Electron Spectroscopy. The sample structure is shown in the inset. Data obtained after 2h exposure to forming gas (5% H_2) at 200 °C.

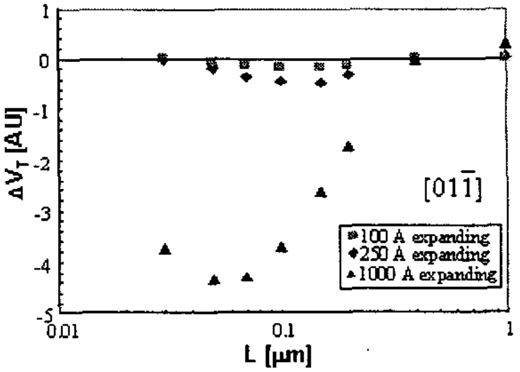

Fig. 8 Calculated ΔV_T vs. gate length for an InP HEMT with a 1000 Å Ti /250 Å Pt /3000 Å Au gate stack and a layer structure consisting of 2000 Å InAlAs/150 Å InGaAs/ 100 Å InAlAs (from bottom to top). Three data sets are shown. In one, the complete Ti layer expands. IN the other two only the top 250 Å or 100 Å of the Ti layer expand.