Electrochemical Degradation Mechanisms in AlGaN/GaN HEMTs

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The last twenty years have witnessed numerous developments in the design and performance of GaN-based high electron mobility transistors (HEMTs). The unique combination of the high critical electric field of wide band gap materials and the existence of a high mobility two-dimensional electron gas (2DEG) allows AlGaN/GaN transistors to be one of the most promising candidates for high power and high frequency applications [1]. Nowadays, the most of the focus of the GaN-based device development has shifted from breaking performance records or designing new device structures to achieving a higher level of device reliability. Various degradation modes have been found to limit the device performance of AlGaN/GaN HEMTs. Unfortunately, there has not been been a consensus on the physical mechanisms nor a clear solution yet on how to overcome the device degradation without de-rating the devices [2][3][4]. The main goal of this talk is therefore to provide physical understanding of some of main degradation mechanisms and provide new approached to solve them.

We have carried out systematic studies on the origin of permanent structural and electrical degradation in AlGaN/GaN HEMTs. Hydroxyl groups (OH^-) from the environment and/or adsorbed water on the III-N surface are found to play an important role in the formation of surface pits during OFF-state electrical stress. The mechanism of this water-related structural degradation is explained by an electrochemical cell formed at the gate edge where gate metal, the III-N surface and the passivation layer meet (Fig. 1). In this electrochemical cell, the gate metal acts as the cathode which provides electrons to the water at the interface between the passivation layer and the AlGaN layer when the gate-to-drain diode is reversed biased. The AlGaN layer acts as the anode and is decomposed and subsequently anodically oxidized in the presence of holes and hydroxyl ions (OH^-). The complete balanced electrochemical reaction is in fact a reduction-oxidation (redox) reaction between AlGaN and water:

$$2Al_xGa_{1-x}N + 3H_2O = xAl_2O_3 + (1-x)Ga_2O_3 + N_2 + 3H_2$$

The relationship between permanent structural and electrical degradation in AlGaN/GaN HEMTs under OFF-state stress has also been studied. Specifically, we have found that the permanent decrease of the drain current is directly linked with the formation of surface pits. One potential mechanism could be that the surface pits decrease the average thickness of the AlGaN barrier, leading to a higher access resistance and a lower drain current. On the other hand, the permanent increase of the gate current is found to be uncorrelated with the structural degradation. One possible explanation for the gate leakage is the migration of gallium ions under the high electric field, which might lead to trap states at the interface of gate metal and III-N layer, and thereby cause an increase in the gate leakage current. Indeed, the out-diffusion of Ga to the gate metal has been observed under TEM EDX mapping analysis (Fig. 2). However, to fully understand this mass-transport process and its association with permanent gate current degradation, more work is still needed in the future.

In the second part of this study, we carried out a systematic analysis on the origin of transient degradation in AlGaN/GaN HEMTs. Water-related redox couples in ambient air are identified as an important source of the surface trapping states, dynamic on-resistance and drain current collapse in AlGaN/GaN high electron mobility transistors (HEMTs). Through *in-situ* X-ray photoelectron spectroscopy (XPS), direct signature of the water-related species — hydroxyl groups (OH^-) are found at the AlGaN surface at room temperature (Fig. 3). It is also found that these species, as well as the dynamic on-resistance, can be thermally removed above 200 °C in high vacuum conditions (Fig. 4**)**. An electron trapping mechanism based on the H_2O/H_2 and H_2O/O_2 redox couples is proposed to explain the 0.5 eV energy level commonly attributed to the surface trapping states as demonstrated in Fig. 8. The role of silicon nitride passivation in successfully removing current collapse in these devices is explained by blocking the water molecules away from the AlGaN surface. Passivation with hydrophobic materials such as Teflon has further been shown to improve the reliability of AlGaN/GaN HEMTs [5].

In conclusions, a mechanism involving water-assisted electrochemical reactions has been proposed to explain OFF-state degradation in AlGaN/GaN HEMTs. These water-related redox couples have also been found to play an important role in the transient degradations in AlGaN/GaN HEMTs. For reliable device performance, future passivation technology should be oriented to further reduce water adsorption and diffusion in GaN-based semiconductors.

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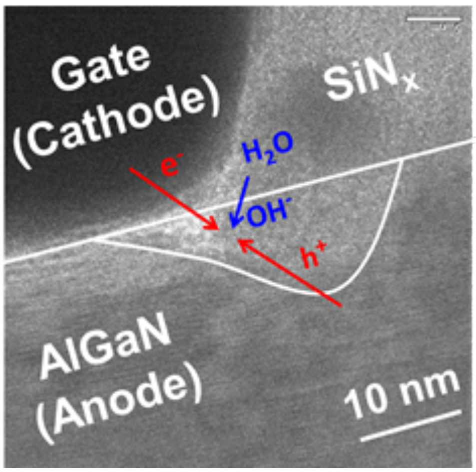

Fig. 1. A Transmission Electron Micrograph (TEM) Image of the electrochemical cell formed at the drain edge of the gate in AlGaN/GaN HEMTs under high OFF-state drain bias.

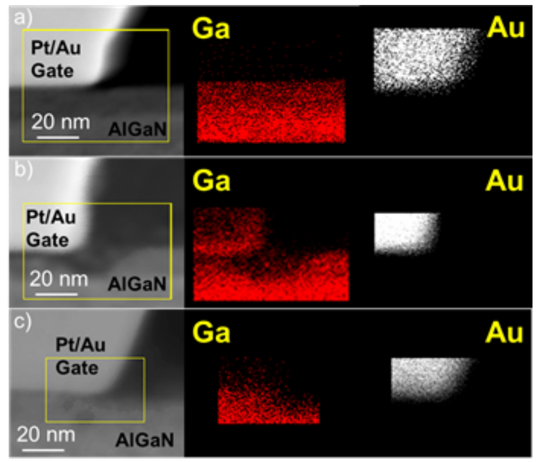

Fig. 2. TEM EDX mapping of gallium (Ga) and gold (Au) at the drain edge of the gate of AlGaN/GaN HEMTs unstressed (a) and stressed at V_{gs} = -7 V and V_{ds} = 43 V for 3000 s in water-saturated Ar (b) and in dry Ar (c).

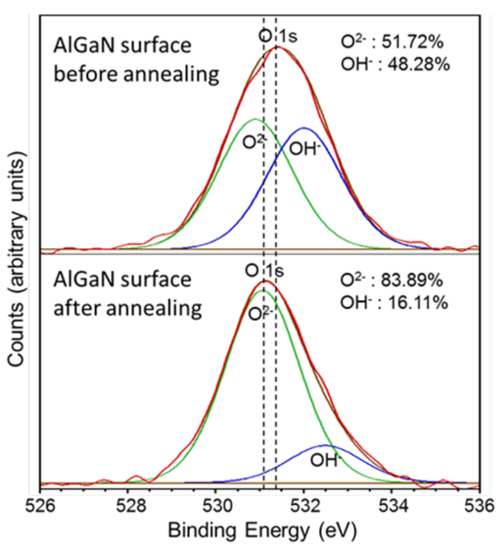

Fig. 3. *In-situ* XPS analysis of the O 1s spectrum on the fresh AlGaN surface before and after vacuum annealing at 300 ºC. The dashed lines show the peak shift of the O 1s core level. The measurements are conducted at room temperature.

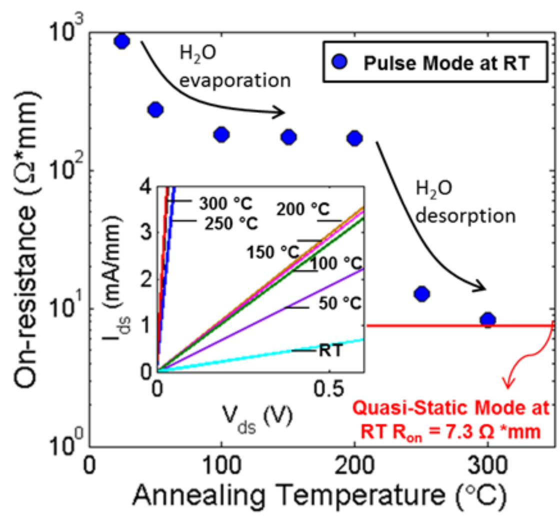

Fig. 4. The on-resistance measured under quasi-static and pulse mode at RT as a function of the annealing temperature. The inset shows the I-V curves in the linear region of the devices annealed at different temperatures in a vacuum of 1×10^{-6} Torr. V_{gs} = 0 V.