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Degradation of AlGaN/GaN Schottky diodes on silicon: Role of defects at the AlGaN/GaN interface

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We report on a detailed investigation of the degradation of AlGaN/GaN Schottky diodes grown on silicon, submitted to high reverse-bias. The analyzed devices have a vertical structure; thanks to this feature, it was possible (i) to characterize the effects of stress by means of capacitance-voltage (C-V) measurements, therefore, identifying and localizing the trap states generated as a consequence of the stress tests; (ii) to accurately control the intensity and distribution of the electric field over stress time. Results indicate that stress induces an increase in the leakage current, which is well correlated to the increase of a new capacitance peak in the C-V characteristics. Based on experimental data and bidimensional simulations, degradation is ascribed to the generation of donor traps in the GaN buffer, close to the AlGaN/GaN interface. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4802011]

Several mechanisms have been proposed as responsible for the degradation of High Electron Mobility Transistors (HEMTs) submitted to high reverse-bias; the generation of pits close to the gate, due to converse piezoelectric effect;[1] the generation of point defects, which can be characterized by Deep Level Transient Spectroscopy;[2] electrochemical reactions, such as oxidation, occurring at device surface;[3] a defect generation and percolation process, due to the generation of trap states in the AlGaN barrier.[4,5] In GaN HEMTs, degradation mostly occurs in proximity of the gate edge, i.e., in the region where the electric field and leakage current have their maxima. Capacitance-Voltage (C-V) characterization represents an accurate technique for the study of the degradation of heterostructure-based devices, since it can provide information on the characteristics and position of the defective states generated after stress within the device structure. However, characterizing the reverse-bias degradation of HEMTs by means of C-V investigation can be very difficult, since the degraded area (edge of the gate) is too small to generate a sufficient variation in the capacitance signal; suitable test structures must be therefore developed to this aim.

The goal of this paper is contributed to the understanding of the degradation processes that occur in AlGaN/GaN-based devices submitted to reverse bias stress, by presenting an extensive study based on combined electrical and capacitive measurements. Thanks to the adoption of specific vertical Schottky diodes—with an n-type layer placed under the undoped channel region—we demonstrate the existence of a degradation process, different from those described in the previous reports on AlGaN/GaN HEMTs (see Refs. 1–4). This process takes place at relatively low voltage levels, consists in the generation of shallow donor traps at the interface between AlGaN and GaN, and determines a gradual increase in the leakage current of the devices.

The samples analyzed within this paper have the structure represented in Figure 1(a); devices are grown on a conductive silicon substrate, and the main heterostructure consists of a 3 nm GaN cap layer, a 22 nm $Al_{0.3}Ga_{0.7}N$ barrier, and a 150 nm unintentionally doped GaN layer. An n-doped GaN layer ($N_D = 4 \times 10^{18}\,cm^{-3}$, 1.7 μm thick) is placed immediately below the undoped GaN layer, with the aim of achieving a vertical current flow when bias is applied between pads A and B (horizontal contact scheme). The analyzed diodes have a Ni/Au Schottky contact, and a round shape; diameters are in the range of 120–600 μm. Devices

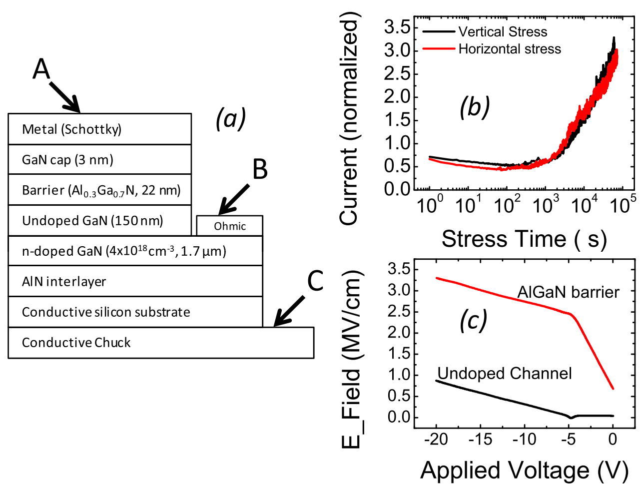

FIG. 1. (a) Schematic structure of the analyzed Schottky diodes. To ensure a vertical current flow, an n-doped GaN layer is placed on bottom of a conventional AlGaN/GaN heterostructure. For the stress experiment, devices can be connected through terminals A and B (horizontal contact scheme), and A and C (vertical contact scheme). (b) Typical degradation kinetics measured by stressing the devices at −12 V. Both the horizontal and the vertical contact schemes give similar results. (c) Variation of the electric field within device structure with increasing reverse voltage level.

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were stressed by applying a negative bias between pads A and B (horizontal contact scheme) or pads A and C (vertical contact scheme). The two contact schemes gave similar stress kinetics (see Figure 1(b)); this result suggests that (independently of the adopted contact scheme) reverse current effectively flows vertically through device structure when a negative bias is applied. This was confirmed by two-dimensional (2D) simulations (not shown here), which indicate that, thanks to the insertion of an n-GaN layer, (i) the electric field has a uniform distribution in the whole area of the devices; (ii) leakage current has a uniform and vertical flow over the area of the diodes. This is different from what happens in a reverse-biased HEMT, where electric field and current flow have their maxima in correspondence of the edge of the gate,[6–8] which—consequently—is the region where most of degradation occurs. Thanks to the uniformity of the electric field, the whole area of the diodes is involved in degradation, and the effects of stress on the heterostructure can be easily studied by means of capacitance-voltage investigation (damage occurs on the whole device area, thus, generating a significant signature in the C-V curves). 2D simulation was used to evaluate the variation of the electric field with increasing reverse voltage; results are shown in Figure 1(c), and indicate that the electric field can be almost linearly controlled by varying the applied reverse bias (beyond the pinch-off voltage).

As a consequence of constant (negative) voltage stress, device current showed an initial, slight, decrease—which can be ascribed to the trapping of negative charge under the gate[5]—followed by a gradual and permanent increase (Figures 1(b), 2(a), and 2(b)); furthermore, during stress time, the noise superimposed to reverse current shows a significant increase (Figure 1(b)). This behavior is very similar to that of GaN HEMTs submitted to reverse-bias stress;[5] results therefore suggest that the vertical Schottky diodes analyzed within this paper and conventional HEMT structures may have similar degradation kinetics and mechanisms.

To achieve a better understanding of the degradation process, we characterized by C-V measurements a number of devices submitted to constant voltage stress test. Typical C-V results are reported in Figure 2(c); the solid curve represents the results collected before stress. With decreasing gate voltage level below 0 V, capacitance keeps a high value around 77 pF—which roughly corresponds to the capacitance of the AlGaN barrier—until pinch-off is reached (−3.8 V). Below the pinch-off voltage, the 2DEG is depleted, and capacitance suddenly drops to its off-state level (here around 15 pF). As shown in Figure 2(c), constant voltage stress induces the generation of a new peak in the C-V curves, centered around −4.4 V. The increase in the amplitude of this peak is well related to the change in the reverse current detected after stress, as shown in Figure 3(a). This result suggests that the two processes (the increase in leakage current and the increase in the new capacitance peak) have the same physical origin. To achieve a better understanding of the degradation process, we carried out 2D simulations by means of ISE-Sentaurus. Results indicate that the generation of the new capacitance peak in Figure 2(c) can be explained by considering that stress induces the generation of shallow donor traps ($E_a \sim 0.1$-$0.3\,\mathrm{eV}$ far from the conduction band) located in the GaN layer, in proximity of the AlGaN/GaN interface; in Figure 3(b), we report the results of simulations carried out by considering different donor concentrations ranging between $10^{11}\,\mathrm{cm}^{-2}$ and $3 \times 10^{11}\,\mathrm{cm}^{-2}$. On the other hand, results (Figures 2(c) and 3(b)) indicate that the modifications of the C-V curves can not be explained by the generation of traps within the AlGaN layer; in fact, the presence of new traps in the AlGaN barrier would result in significant variation in the pinch-off voltage of the devices, and this was not detected by C-V analysis (see Figure 2(c)).

Based on the experimental results and simulations described above, the following model was developed to explain the degradation of AlGaN/GaN vertical Schottky diodes. When a negative bias is applied to the devices, the 2DEG is fully depleted, and leakage current starts to flow—possibly via trap-assisted tunneling—from the gate contact to the GaN channel layer (Figure 4(a)).[5] The trapping of negative charge within the AlGaN layer may determine a slight decrease in leakage current (see Figure 1(b)). For longer stress times, shallow donor traps may be generated in the GaN buffer (near the AlGaN/GaN interface), due to the injection of accelerated electrons towards the AlGaN/GaN

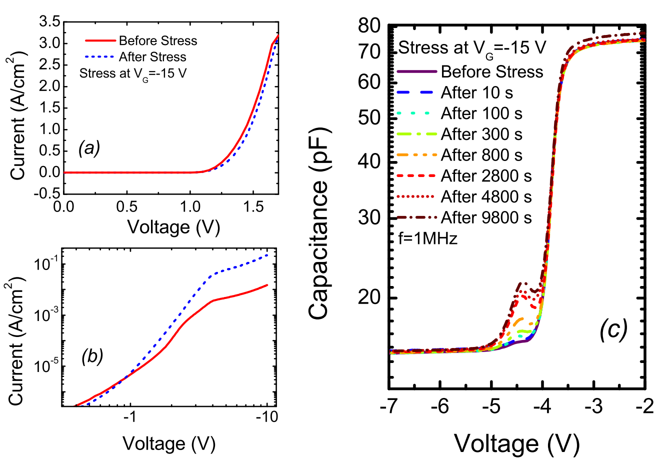

FIG. 2. (a) and (b) I-V measurements taken before and after the stress at −15 V, 9800 s, on one of the analyzed samples, in the forward and reverse-bias regions. (c) C-V measurements taken on the same device during stress time.

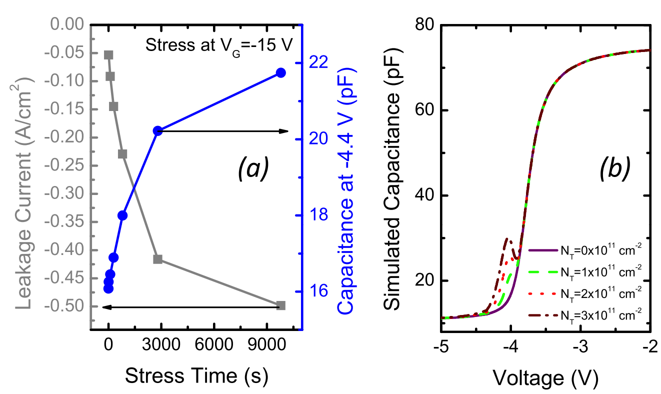

FIG. 3. (a) Variation of leakage current and peak capacitance measured during stress at −15 V on one of the analyzed samples. (b) C-V curves simulated by considering different concentrations of traps located in the GaN buffer, in proximity of the AlGaN/GaN interface.

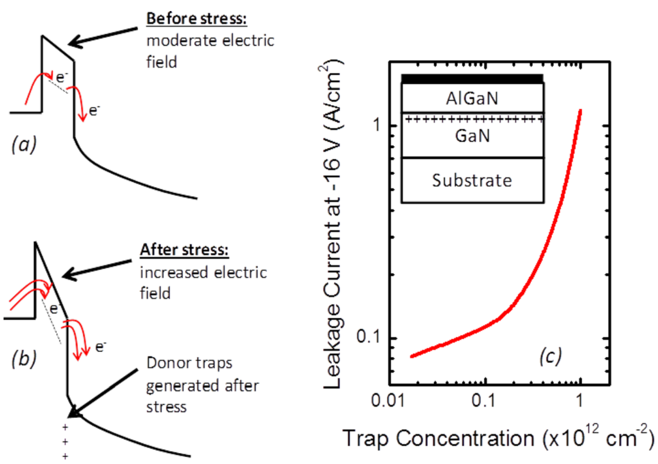

FIG. 4. (a) and (b) A schematic representation of the model used to explain the increase in leakage current (diagrams not in scale, the 3 nm GaN cap is not represented for simplicity). (c) Simulated variation in the leakage current of the analyzed devices induced by an increase in the concentration of shallow donor traps located at the AlGaN/GaN interface (without considering any modification in the conductivity of the AlGaN layer).

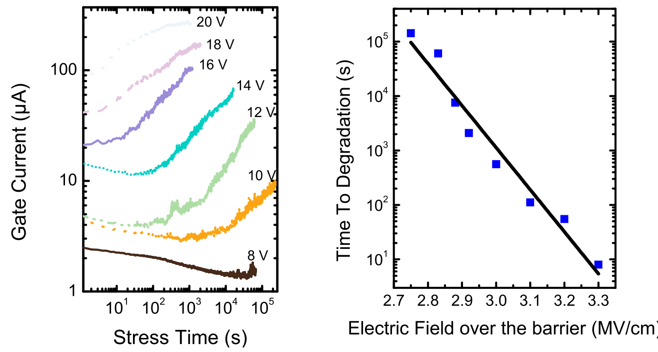

FIG. 5. (a) Variation of the leakage current of several identical Schottky diodes submitted to stress at different voltage levels. (b) Dependence of the time for degradation (time necessary for a 50% increase in leakage current) on the electric field over the AlGaN barrier.

interface, and/or to the high electric fields. This may determine an increase in the electric field over the AlGaN barrier, and consequently an increase in the reverse leakage current (Figure 4(b)). 2D simulations were carried out to confirm this model; results (Figure 4(c)) indicate that, simply due to an increase in donor density at the AlGaN/GaN interface, leakage current can show a remarkable increase, due to the increase in the electric field over the AlGaN barrier (Figure 4(b)). Remarkably, the simulations indicate that the increase in leakage current may occur even without considering any modifications in the conductivity of the AlGaN layer arising as a consequence of the stress; the degradation mechanism found within this paper is therefore different from those described in the previous reports (see Refs. 1–5), where an increase in leakage current was always ascribed to the increase in the conductivity of the AlGaN barrier, due to the generation of defects.

As described above, the degradation mechanism detected within this paper consists in the generation of donor traps in the GaN channel region, close to the AlGaN/GaN heterointerface. This degradation process was detected in large-area Schottky diodes, since in these devices, thanks to the vertical current flow and to the uniform distribution of the electric field, the whole device area degrades after stress generating a unique signature in the C-V curves (Figure 2(c)). This mechanism can be difficult to detect in GaN HEMTs, due to the small area of the damaged region; nevertheless, experimental evidence collected within this work suggest that this mechanism can play a role also in limiting the reliability of GaN HEMTs, and prepare the way for further studies in this area.

According to the interpretation given above, the degradation process described within this paper has a strong dependence on the electric field; this hypothesis was confirmed by subjecting a number of identical devices to stress at different voltage levels. Results (Figure 5(a)) indicate that an increase in the stress voltage determines an acceleration of the stress kinetics; time-to-degradation (time necessary for a 50% increase in leakage current) was found to have an exponential dependence on the electric field applied to the devices during stress (Figure 5(b)).

In summary, in this paper, we have described a study of the degradation of AlGaN/GaN Schottky diodes submitted to constant voltage stress. Differently from conventional HEMT structures, the vertical devices analyzed within this paper allow to evaluate the exact dependence of the failure kinetics on the electric field, and to analyze the degradation mechanisms by means of C-V measurements. Results indicate that devices may show a gradual degradation, which is ascribed to the creation of donor defects in the GaN buffer, close to the AlGaN/GaN interface. This process determines an increase in the leakage current of the devices, due to the increase in the electric field over the AlGaN barrier.

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