Direct monitoring of hot-carrier accumulated charge in GaN HEMT and PHEMT devices

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Abstract

A contactless methodology of directly monitoring walkout phenomena in HEMT devices has been demonstrated for PHEMT and GaN HEMT devices. No walkout phenomena have been observed in GaN HEMT, while evolution of the surface photovoltage spectra (SPS) indicates accumulation of the positive electrical charge the buffer and surface layer of device, after RF power stress. In PHEMT, walkout phenomena are due to the accumulation of the charge at surface traps, which have been introduced during manufacturing process. The SPS make it easy to monitor this charge accumulation during RF power stress.

INTRODUCTION

Hot carriers play an essential role in a wide variety of modern electronic devices. Under actual operational conditions, these carriers often cause generation and/or accumulation of electrical charge at localized electronic states in the device. These states are either imperfections in the original epi-structure or/and defects induced during the manufacturing process. The localized charge leads to a ‘new’ potential landscape in a device, and it manifests itself in shifts of the DC/RF device parameters - “walk-out/in” effects. The challenge is to develop a non-destructive technique, which may be applied a complete chip level, making it possible to define a location of accumulated charge in a device.

Surface Photovoltage Spectroscopy (SPS) is a powerful tool for monitoring electric fields in HEMT structures, including PHEMT, MHEMT and GaN HEMT. SPS is a method, which fulfills most of the demands for comprehensive transistor structure characterization and for incoming wafer inspection.[1] SPS monitors changes in the semiconductor surface work function induced by absorption of monochromatic light, giving rise to surface photovoltage (SPV). The high sensitivity of this technique may be used to define whether the charge is localized at surface or in buffer layer.

The aim of this research is to develop a methodology for direct monitoring of walk-out/in phenomena in GaN HEMT and PHEMT devices. The SPS based monitoring is evaluated on PHEMT devices, demonstrating high sensitivity of this method and providing a clear physical picture of the phenomena. The methodology applied to GaN HEMT advanced devices shows high quality of the production process, with no induced imperfections during the manufacturing process.

EXPERIMENTAL

A 0.25 μm gate power PHEMT was used as the basic element for this research. The main process steps include: A double heterostructure GaAs/AlGaAs/InGaAs MBE-grown initial wafers, which incorporate double Si planar delta doping, conventional alloyed AuGeNiAu, Ohmic contacts, and a double-recessed sub-micron T-gate. The vertical structure was determined by two versions with a different screen layer thickness – (D_S). Version EI has an 8 nm thick screen layer and version EII has a 15 nm thick screen layer.

AlGaN/GaN HEMTs are also investigated. The epi-structure is unintentionally doped AlGaN/GaN on SiC substrate. The epitaxial layer was grown using metalorganic chemical vapor deposition (MOCVD). The device mesa isolation was etched using a $BCl_3\backslash Cl_2\backslash Ar$ gas mixture in ICP; A Ti/Al/Ni/Au metal stack followed by alloying at 900^oC for 30 sec formed Ohmic contacts. Ni/Au was used as Schottky gate followed by silicon nitride as a passivation layer. Electroplating of thick Au was used for supporting high currents and for connecting device areas by air-bridging.

A detailed description of SPS and its applications may be found in Ref. [2]. This technique has been successfully applied for characterization of novel structures and devices [3-7].

SPS is performed before and after each step of the electrical measurements in order to monitor changes in the potential profile of a device under test. The evolution of SPV spectra during an experiment may be decoded in terms of accumulation of the electrical charge at imperfections in the structure, if any. There are three groups of electrical measurements: 1) Small-Signal and drain-source current as a function of gate-source voltage at a constant drain-source voltage of 2 V; 2) Drain-source current as a function of gate-source voltage at a constant drain-source voltage of 8 V; 3) Drain-source current as a function of gate-source voltage at a constant drain-source voltage of 2 V. Figure 1 shows I-V curves under the operational conditions 1 and 3 for a PHEMT on the epitaxial structure EI. Figure 2 shows I-V curves under the operational condition 2 for a PHEMT on the epitaxial structure EI. For IV measurements of version EII, the same negative gate current is observed under the operational condition 2, but there is no difference between I-V curves under conditions 1 and 3.

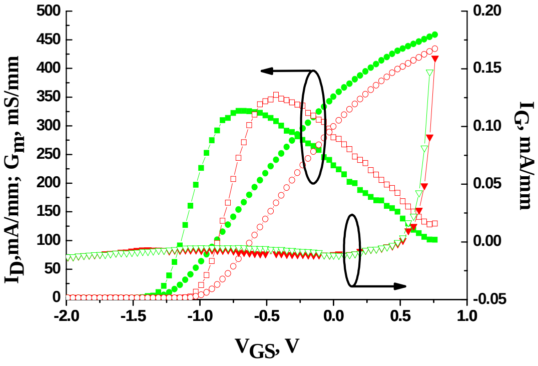

Figure 1. I-V curves under operational conditions 1 and 3 for a PHEMT on the epitaxial structure EI

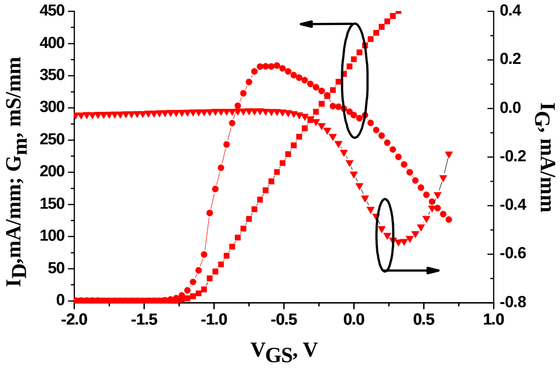

Figure 2. I-V curve under operational condition 2 for a PHEMT on the epitaxial structure EI

During measurement at operational condition 2 (Figure 2), a negative gate current is observed, under some of operational conditions. This unambiguously indicates impact ionization processes within the structure, which lead to generation of electron-hole pairs

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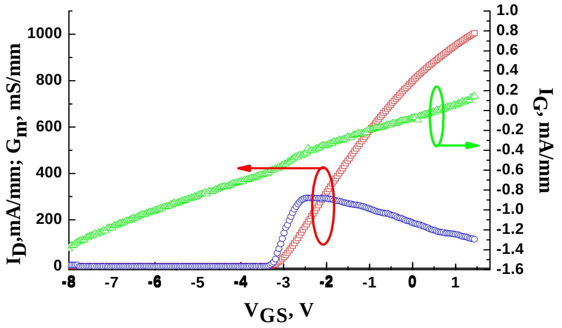

Figure 3. I-V curve of a GaN HEMT under operational condition 1.

Figure 3 shows I-V curves of a GaN HEMT under operational condition 1. There are no changes in electrical performance after operational conditions 2 and insignificant decrease in gate current (not shown here) after operational conditions 3. It should be stressed that a negative gate current has been measured during large signal measurements. However, in the case of GaN HEMT, impact ionization does not leads to pronounced walkout phenomena in HEMT performance.

All measurements are performed on the wafer using a HP 4155C semiconductor analyzer and a 8510C network analyzer. The statistical analysis of the data was carried out using SAS software (JMP 5.0).

The SPS measurements are performed in air using a commercial Kelvin probe unit (Besocke Delta Phi, Julich, Germany). The optical system consists of a 250-W tungsten-halogen lamp, a double monochromator (McPherson, USA) and a set of band pass filters to avoid second order harmonics. The measurement sensitivity is about 1 mV and the light intensity is inthe order of 10 µW/cm^2 at a wavelength of 750 nm. Neutral density filters control the light intensity.

RESULTS AND DISCUSSION

A. Direct monitoring of walk out in PHEMT

SPS makes it possible to monitor the evolution of the electric field distribution within a device as a function of operational conditions. In SPS, the change in the contact potential difference (CPD) between a reference gold electrode and a semiconductor surface is monitored as a function of photon energy. The total signal is a combination of signals from all the structure layers penetrated by light. The signal magnitude is a complicated function of light absorption and electric fields in any absorption region. The two oppositely directed electric fields in the buffer and Schottky layer define the potential profile of the structures. Since CPD is sensitive to the electric field direction, the CPD signals resulting from the buffer and Schottky layers are of opposite signs (positive from buffer and negative from Schottky layer). The total signal is a combination of the two signals.

Absorption of light in the quantum well (QW) creates electron-hole pairs. While electrons are confined to the QW by fields in the buffer and Schottky layers, holes are likely to overcome the QW-Schottky layer interface or the QW-buffer interface potential barrier. The holes are swept by the electric field in the buffer or in the Schottky layer direction, contributing to signals with opposite signs.

A PHEMT device is used as a test case, where the CPD spectrum is measured: 1) on a bare device, i.e., before voltage application; 2) on the same device after measurement of small signal parameters at a drain-source voltage of 2 V; 3) in the same device after measuring drain-source current as a function of gate-source voltage at a drain-source voltage of 8 V. In the last case, a negative gate current is observed, which is due to impact ionization within the structure, which leads to generation of electron-hole pairs.

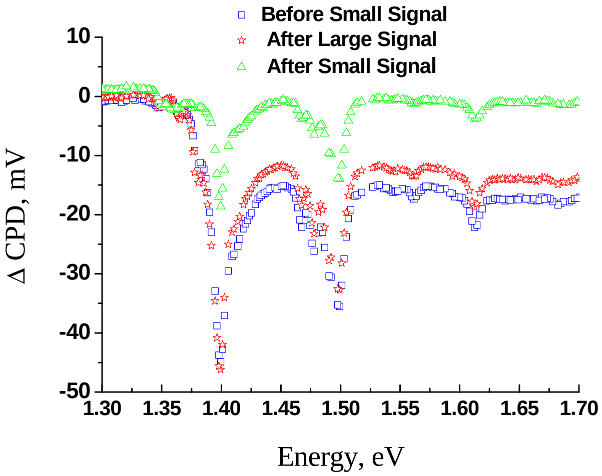

Fig. 4. Evolution of CPD spectra of a PHEMT on structure EI under various operational conditions: squares - bare device; triangles - after exposure to small signal conditions; stars - after impact ionization

Figure 4 shows the evolution of SPV spectra under operational conditions 1-3 for a PHEMT on the epitaxial structure EI.

The first peak indicates the interplay of signals from the buffer and Schottky layers as a result of light absorption in the channel (InGaAs). In the case demonstrated in Fig. 4, the signal from Schottky layer is dominant, which results in a negative total CPD. When the signal from the Schottky layer is saturated, the total CPD changes sign.

There is no change observed in the spectral shape of these 3 curves while the spectrum amplitude is clearly a function of the conditions: the highest absolute value of the first peak for the bare device (squares in Fig. 4) is significantly reduced during small signal measurements (triangles in Fig. 4) and increases again after exposure to hot electrons and holes in case 3 (- stars).

For the version EII structure (Figure 5), the evolution of the SPS spectrum is similar to the ones of EI for the first two steps, while there is no change in amplitude between measurements 2 and 3.

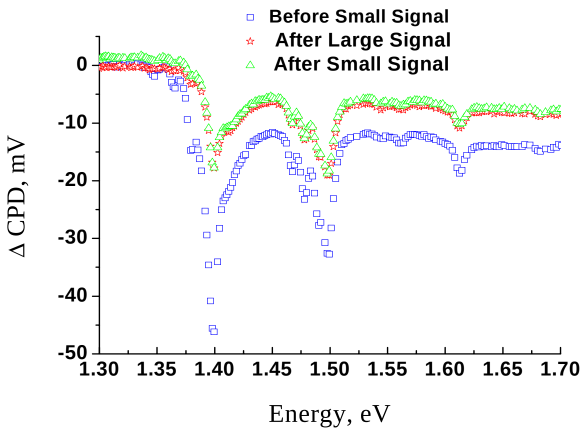

Fig. 5. Evolution of CPD spectra of a PHEMT on structure EII under operational conditions: squares - bare device; triangles - after exposure to small signal conditions; stars - after impact ionization

The evolution of the spectra may be explained within the framework of traditional SPS consideration. During small signal measurements, the device is driven to an open state, where the device surface is exposed to hot electrons. These carriers are trapped at the surface, which becomes more negative compared to the bare device, reducing the SPS signal.

The following large signal measurements induce electron-hole generation, while holes are driven by the electric field towards either the surface or/and the buffer. Again, trapping holes at surface states makes the device surface more positive, leading to increase of the SPS signal. For version EII, there is no change in the SPS signal due to differences in the epi-structure with better screening capabilities.

Thus, the evolution of SPS spectrum indicates significant imperfections, which are due to some steps in PHEMT process. The imperfections behave both as electron and hole traps. It is shown that variations in the epi-structure may reduce the effect of accumulated charge at the device surfaces.

B. SPS of GaN HEMT

Following the experimental steps in the previous section, SPS of a GaN HEMT on SiC substrate has been performed. There is no change in the spectral shape of the 2 curves. Moreover, no change is observed in the amplitude of the spectra at the bare device and in the one after small signal. Figure 6 presents SPS spectra measured at initial state and after small and large signal electrical measurements.

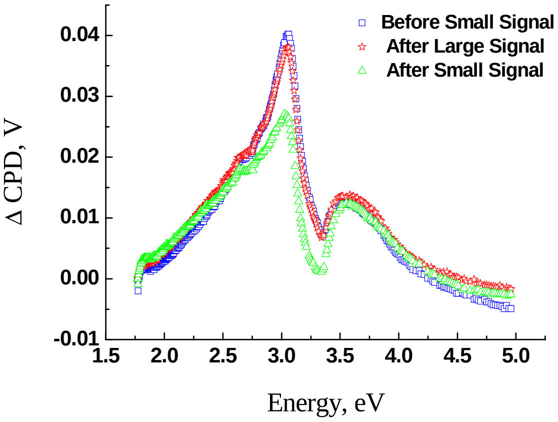

Fig.6. Evolution of CPD spectra of a GaN HEMT under operational conditions: star - bare device; squares - after exposure to small signal conditions;

SPS spectrum taken after large signal measurements shows reduction in amplitude of the signal at 3 eV. In the region between 3-3.5 eV, the decrease in the signal becomes more moderate, compared to the bare structure. Both effects indicate reduction of the electric fields in the surface and buffer regions, which may be explained by accumulation of a positive electric charge at the imperfections at the surface and within the device buffer. [7].

These imperfections behave as hole rather electron traps, while defects in the buffer are introduced during the wafer growth. Additional study will show whether imperfections at the surfaces are induced by manufacturing or by growth processes.

CONCLUSIONS

A methodology of directly monitoring walk out phenomena in HEMT devices has been demonstrated for PHEMT and GaN HEMT devices. The evolution of photovoltage spectra indicates the presence of two types of traps for electrons and holes in PHEMTs, which were induced during the manufacturing process.

No pronounced walk out/in phenomena in GaN HEMT have been detected during electrical testing. However, a SPS study of the GaN HEMT shows presence of accumulated positive charge at traps in both the surface and buffer layers. These traps are populated during impact ionization, which is induced during power measurements.

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ACRONIMS

CPD: Contact Potential Difference
D_S: Screen Layer Thickness
HEMT: High Electron Mobility Transistors
MOCVD: Metalorganic Chemical Vapor Deposition
PHEMT: Pseudomorphic High Electron Mobility
SPS: Surface Photovoltage Spectroscopy