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Photoreflectance investigations of a donor-related transition in AlGaIn/GaN transistor structures

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Below-bandgap photoreflectance (PR) features observed for GaN layers and undoped AlGaIn/GaN transistor structures have been analyzed in this letter. In addition to PR signal associated with the interference oscillations a strong PR feature at ~ 3.37 eV has been resolved for some AlGaIn/GaN structures. This feature has been attributed to an electron transition between the valence band and a donorlike state located ~ 50 meV below the conduction band. An absorption-type experiment, such as PR spectroscopy, makes it possible to observe such a transition because this donorlike state is ionized by the strong internal electric field existing in the GaN layer at the AlGaIn/GaN interface. The existence of this electric field with a magnitude of ~ 210 kV/cm has been confirmed by the observation of GaN-related Franz-Keldysh oscillations in the PR spectra. Obtained results show that donorlike states located ~ 50 meV below the conduction band are one of the sources of high concentration of the two dimensional electron gas in undoped AlGaIn/GaN transistor structures.

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Photoreflectance (PR), as a contactless form of modulation spectroscopy, is a powerful technique for studying and characterizing many of the important parameters of bulk/thin film semiconductors, semiconductor surface/interfaces, semiconductor microstructures, and actual device structures.¹⁻⁴ In this technique the periodic modulation of the built-in electric field by photo generated electron-hole pairs produces sharp, derivativelike features corresponding to interband transitions. These features appear near energies at which an electron can make a transition from an occupied state in the valence band to an unoccupied state in the conduction band. The sensitivity of this method is about three to four orders of magnitude higher than common absorption measurements. However, transitions related to defect states are rarely observed in PR spectra, because this technique is sensitive to the density of states as each absorption-type technique. The density of states associated with energy levels within band gap is usually few orders smaller than the density of states associated with the critical points of the band structure. Therefore, the PR spectroscopy is dedicated to study mainly the interband transitions and not to study the below-band gap transitions associated with defect states or impurities. Defect related (DR) transitions are usually studied in emission-type techniques, e.g., photoluminescence (PL) which is very sensitive to defect states and has been applied to study GaN-based structures many times.⁵ For this reason PR measurements in transparency regions of samples (i.e., below the band-gap energy) are rarely performed and below-band gap PR features are almost not discussed in the literature. The aim of this article is to analyze PR features observed below GaN band gap on GaN layers and AlGaIn/GaN transistor structures.

AlGaIn/GaN heterojunction field-effect transistors (HFETs) have emerged as attractive transistors suitable for

high-power and high-temperature electronics.⁶ Large piezoelectric and spontaneous polarization fields occurring in the AlGaIn/GaN heterostructures generate a triangular well at the interface.⁷ The nominally undoped (Al)GaN compounds are mostly *n*-type, hence electrons from the region of the barrier close to the interface are depleted and a two dimensional electron gas (2DEG) is accumulated in the triangular-shaped potential. In this way, the 2DEG appears in AlGaIn/GaN heterostructures without doping.⁷ However, the exact origin of the electron gas is still unclear and under debate.

PR spectroscopy is widely used to study the value of the built-in electric field in AlGaIn/GaN structures.⁸⁻¹³ The knowledge on PR features possible to observe in these structures is very useful, because in addition to the information on the electric field extra information on the band structure or the optical quality can be extracted from PR measurements. In this letter we focus on the below-band gap region. So far, PR features in this spectral range have been observed by different authors^{10,11,14-16} but usually they have not been analyzed. We show here that defect-related transitions as well as oscillation-like features associated with modulation of the refractive index in the GaN layer can be observed in PR spectra. The intensity of the two PR signals depends on the GaN layer thickness as well as other factors which are discussed in this work.

The GaN layers were deposited on 2 in. diameter, (0001)-oriented and commercially available sapphire substrates by metalorganic chemical vapor deposition using a RF heated AIXTRON AIX-200 low pressure horizontal reactor. Trimethylgallium and ammonia were used as Ga and N precursors, respectively. The growth procedure was started by annealing the substrate for 5 min at high temperature (1100 °C) in a H₂ atmosphere at a total reactor pressure of 350 mbar. Then the carrier gas was changed to N₂ keeping all other parameters constant. Next, a 45 s nitridation step

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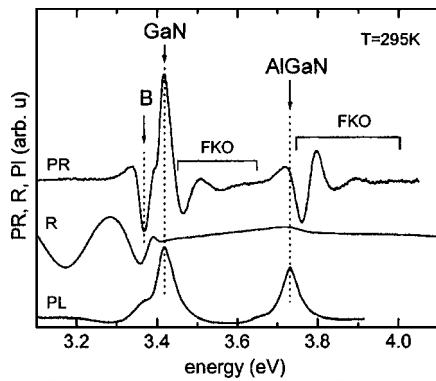


FIG. 1. A comparison of PR, R, and PL for an $\text{Al}_{0.21}\text{Ga}_{0.79}\text{N}/\text{GaN}$ HFET structure; the thickness of AlGaN layer is 43 nm.

was carried out using 2 slm of NH_3 at a temperature of 1110 °C and pressure of 50 mbar. After the nitridation, the temperature was decreased to 525 °C, the pressure raised to 540 mbar and a thin GaN nucleation layer (NL) was deposited for 3.5 minutes. Next, the wafer was brought to high temperature (1170 °C) and annealed for 70 s at 35 mbar reactor pressure. In this step the recrystallization of the crystallites in NL takes place.¹⁷ Finally, a GaN epilayer was deposited at a total reactor pressure of 35 mbar and temperature 1170 °C with a V/III ratio of about 1900 and H_2 as a carrier gas. AlGaN/GaN transistor structures have been grown at the same growth conditions. The AlGaN top layer was grown at 1170 °C and pressure of 35 mbar. For PR, photoluminescence (PL) and reflectance (R) measurements standard set-ups were used.^{4,12}

Figure 1 shows PR, R, and PL spectra of an AlGaN/GaN heterostructure obtained at room temperature. The PL spectrum exhibits two peaks at 3.42 and 3.73 eV which are associated with the band gap-related transitions in GaN and AlGaN layers, respectively. In the transparency region for this sample (<3.42 eV) the R spectrum exhibits typical below-band gap oscillations attributed to an interference effect inside the epitaxial layers. Moreover, above the GaN band gap, at ~ 3.73 eV, a peak associated with a band-to-band absorption in the AlGaN layer is observed.

PR is a differential form of R, hence its sensitivity is much higher, as can be seen in Fig. 1. In this case, transitions originating from both GaN and AlGaN layers are very well visible. The AlGaN-related resonance is followed by strong Franz-Keldysh oscillations (FKOs),¹⁻⁴ which are associated with the presence of an internal electric field in the AlGaN layer. Weak FKOs are also observed for the GaN-related signal. The built-in electric field determined for GaN layer from the FKO period is ~ 210 kV/cm. In addition, an extra PR feature (labeled as B) is observed at ~ 3.37 eV. Note that this signal is observed in the transparency region for the sample. This fact indicates that this signal derives from DR transitions or other phenomena. In order to explain the origin of this line a detailed analysis of PR spectra for many GaN layers and AlGaN/GaN structures has been performed.

Figure 2 shows PR spectra for AlGaN/GaN structures and a PR spectrum for a representative GaN layer. The line B is very well observed for AlGaN/GaN structures shown in Fig. 2(a), i.e. a set of samples with the same thickness of the AlGaN (~ 44 nm) and GaN ($0.6 \mu\text{m}$) layers but with different Al content of the AlGaN layer (see the content in the figure caption). This line has been also observed for other

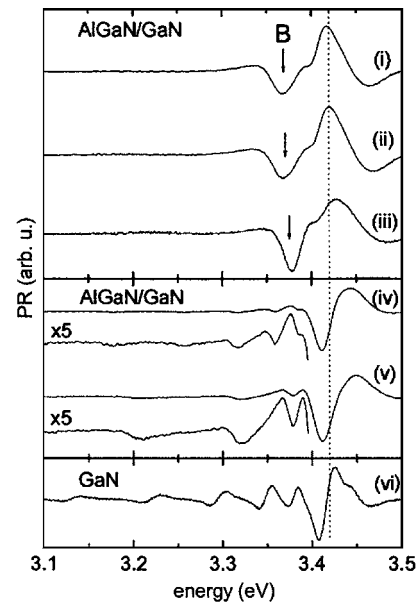


FIG. 2. PR spectra of AlGaN/GaN transistor structures with different content and thickness of AlGaN layer: (i) $\text{Al}_{0.29}\text{Ga}_{0.71}\text{N}(44 \text{ nm})/\text{GaN}(0.6 \mu\text{m})$, (ii) $\text{Al}_{0.26}\text{Ga}_{0.74}\text{N}(44 \text{ nm})/\text{GaN}(0.6 \mu\text{m})$, (iii) $\text{Al}_{0.21}\text{Ga}_{0.79}\text{N}(43 \text{ nm})/\text{GaN}(0.6 \mu\text{m})$, (iv) $\text{Al}_{0.33}\text{Ga}_{0.67}\text{N}(25 \text{ nm})/\text{GaN}(2 \mu\text{m})$, and (v) $\text{Al}_{0.30}\text{Ga}_{0.70}\text{N}(20 \text{ nm})/\text{GaN}(1 \mu\text{m})$; and (vi) a GaN layer.

AlGaN/GaN samples but its intensity was usually much weaker than the PR signal associated with the band gap-related transitions in GaN layer and PR signal associated with interference oscillations. These oscillations are often observed for GaN-based structures and they could superimpose with the signal associated with DR transitions, thereby the line B could be not resolved.

Figure 2(b) shows PR spectra for selected AlGaN/GaN structures with the thickness of AlGaN and GaN layers different than in the previous set of samples (see details in the figure caption of Fig. 2). For samples shown in this figure the line B is not resolved because PR features related to interference oscillations are visible in this spectral region. Also for GaN layers the PR signal observed below-band gap is associated with the interference oscillations, see in Fig. 2(c). The origin of the interference oscillations observed in PR spectra is a modulation of the refractive index in the GaN layer due to the generation of additional carriers by the modulated beam¹⁸ and other phenomena. Figure 3 shows a comparison of PR spectrum of the GaN layer with the R spectrum and its derivative. As it is seen in this figure the part of PR spectrum below the GaN band gap energy (3.42 eV) corresponds to the derivative of R spectrum. Very similar results have been obtained for other GaN layers and AlGaN/GaN structures shown in Fig. 2(b) but not for AlGaN/GaN structures shown in Fig. 2(a). Finally, it has been concluded that the below-band gap PR signal in GaN-based structures is usually associated with the interference oscillations, because the PR signal related to DR transitions is weaker than remaining PR signals. However, for some samples the DR transition is strong and can be very well resolved in PR spectrum.

The intensity of a DR transition observed in PR spectroscopy depends on the concentration of defect states and their optical activity. In the case of GaN-based structures, the concentration of native defects is usually high in comparison to other e.g. GaAs-based structures. Moreover, a lot of different defect states close to the conduction band as well as the valence band are possible for GaN.^{5,6} Thus, transitions

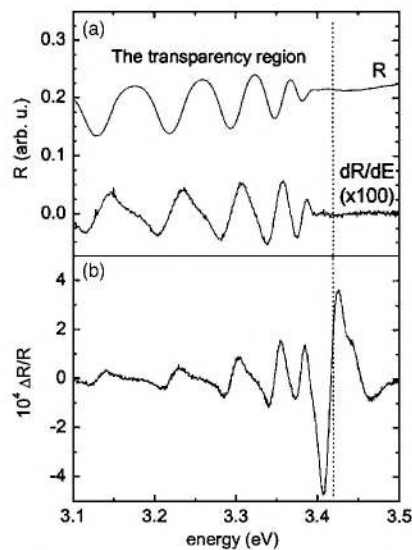


FIG. 3. (a) R spectrum of a GaN layer with its derivative (dR/dE). (b) PR spectrum of the GaN layer.

associated with different defect states are expected in PR spectra for GaN-based structures. However, the DR transition is active in PR spectroscopy if an electron can be transferred between the valence band and the defect state (the defect state and the conduction band). Such a situation is possible if the donorlike (acceptorlike) state is not occupied by an electron (a hole). In the case of AlGaIn/GaN transistor structures, GaN layer at the interface is depleted from electrons due to the strong internal electric field. In this way some donorlike states are ionized and they are active in PR spectroscopy. Note that such a situation does not take place for GaN layers. Therefore, we suppose that B transition observed in our samples could be attributed to the DR transition between the valence band and a donorlike state located ~ 50 meV below the conduction band. For GaN layers without a significant internal electric field this donorlike state is not ionized at room temperature due to too low thermal energy. Therefore, a transition involving this state is not observed in PR for our GaN layers. However, for AlGaIn/GaN transistor structures the donorlike states located 50 meV below the conduction band is ionized by the high internal electric field existing in GaN layer at the AlGaIn/GaN interface. The value of this field depends on the thickness of layers in AlGaIn/GaN structures. Therefore, the intensity of B transition varies with the thickness of the GaN layer such as it has been observed for our samples. In our case, good conditions for the observation of the B transition have been found for samples shown in Fig. 2(a). In this case the interference oscillations do not interfere with PR signal associated with DR transitions because these oscillations have long period and are very weak.

For samples shown in this letter the change in the intensity of B transition which is associated with possible changes in the concentration of native defects can be neglected, because all samples were grown at the same conditions and hence all samples should have similar concentration of native defects. However, the activity of these states in PR spectroscopy could vary from sample to sample, because the band bending at AlGaIn/GaN interface depends on the layer thickness and the content of AlGaIn layer.^{7,12}

In addition, an electron transition between an acceptorlike state occupied by electron and the conduction band

should be considered for our samples. We do not exclude such a transition for our samples, because for n-type GaN layers with donorlike and acceptorlike states, such absorption process is very probable. However, we suppose that the intensity of such a transition is very weak due to low concentration of acceptorlike states in our structures.

In conclusion, a well resolved PR resonance at ~ 3.37 eV has been found for a set of AlGaIn/GaN transistor structures. This line has been attributed to an electron transition between the valence band and the donorlike state located ~ 50 meV below the conduction band. The observation of this transition is possible for AlGaIn/GaN transistor structures because the donorlike states near the AlGaIn/GaN interface are ionized due to strong internal electric field (~ 210 kV/cm) existing in GaN layer at the interface. The presence of such donorlike states in GaN layer is one of the origin of the high concentration of the 2DEG in undoped AlGaIn/GaN transistor structures. Moreover, PR features associated with the interference oscillations have been observed for AlGaIn/GaN structures and GaN layers. These features could superimpose with the defect-related transitions, therefore the latter one are not always resolved in PR spectra.

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