Investigations of GaN surface quantum well in AlGaN/GaN transistor heterostructures by contactless electroreflectance spectroscopy

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AlGaN/GaN transistor heterostructures, caped by ~2 nm GaN layer, were investigated by contactless electroreflectance (CER) spectroscopy at room temperature. Below the AlGaN-related transition CER spectra have shown a clear resonance at the energy of ~3.7 eV, i.e., at much higher energy than the GaN band gap energy. The observed feature has been connected with the optical transition within the GaN cap layer. It was concluded that a surface GaN quantum well has been created by the deposition of nominally undoped (or Si-doped) GaN cap layer on AlGaN/GaN transistor heterostructures. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2399372]

In typical quantum well (QW) systems, the materials of the well and both barrier layers are semiconductors. As it was demonstrated on the example of the GaAs-based,[1–5] SiGe-based,[6] and ZnO-based systems,[7] the replacement of one of the barriers with the vacuum level may also lead to an efficient confinement.

GaN and related nitrides are very attractive materials for the fabrication of high-temperature, high-power, and high-frequency field effect transistors (FETs).[8] This is due to the wide band gap, high thermal stability, and high breakdown voltage that are better suited for these purposes than GaAs-based heterostructures and other common III-V based semiconductor heterostructures. To control and improve some of the physical and electrical properties of GaN-based high electron mobility and power transistors (HEMPTs), a thin GaN cap layer is deposited on the HEMPT layer stack.[9–11] This deposition can produce a surface QW. In this kind of systems, the confining potential is obtained from one side by the vacuum level, which is defined approximately by the electron affinity (~2.7–4.1 eV,[12,13]) and from the other side by the band gap discontinuity between the GaN and AlGaN semiconductor materials. As far as we know, optical emission from the surface GaN QW was demonstrated only by Muth *et al.*[14] The electromodulation technique, such as contactless electroreflectance (CER), is very suitable for investigations of semiconductor heterostructures due to its high sensitivity to the density of states even at room temperature.[15,16] Moreover, the contactless and nondestructive character enables the investigation of phenomena which are associated with the surface and interfaces in semiconductor structures. As far as we know, the CER technique has never been used to study surface QWs. In this letter we have applied CER technique to study the optical transitions in AlGaN/GaN transistor heterostructures with a thin GaN cap layer, which creates a surface QW.

The investigated structures were grown on (0001)-oriented commercially available sapphire substrate by metal organic chemical vapor deposition using a radio frequency (rf) heated, AIXTRON AIX-200, low pressure horizontal reactor. Trimethylgallium, trimethylaluminum, ammonia, and silane were used as Ga, Al, N, and Si precursors, respectively. Four samples were investigated in this letter, all with Ga-face polarity. The first one (S1) is a heterostructure consisting of a single $Al_{0.27}Ga_{0.73}N$(26.9 nm)/GaN(2 μm) heterojunction. The second one (S2) is a modified heterostructure consisting of a thin AlN ($d \sim 1.5$ nm) spacer layer between the AlGaN and GaN layers. The third (S3) and fourth (S4) structures have a single AlGaN/GaN heterojunction with the AlN spacer layer but, in addition, have thin undoped and Si-doped GaN cap layers, respectively. The structural quality of the epitaxial layers was assessed by taking the full width at half maximum of the symmetric [002] and asymmetric [105] low angle diffraction peaks of the rocking curve obtained by a high resolution x-ray diffractometer (Bruker-D8 instrument). In this way the good structural quality of all the investigated samples has been confirmed. The capacitance-voltage and Hall experiments have been performed at room temperature to determine the two dimensional electron gas (2DEG) concentration and mobility. For investigated structures the 2DEG concentration is in the range of $(7.4–8.1) \times 10^{12}$ cm^{-2}. The Hall mobility is >1300 cm^2/V s for structures S3 and S4, 1120 cm^2/V s for structure S2, and 713 cm^2/V s for structure S1.

In order to measure the CER spectra a so-called bright configuration of the experimental setup has been used.[17] Sample was illuminated with the 250 W halogen lamp. Reflected light was dispersed by a single-grating 0.55 m focal-length Jobin-Yvon monochromator with the resolution of several meV. The CER signal was detected by the Hamamatsu R647 photomultiplier using the lock-in technique. Samples were mounted inside an open air capacitor with one semitransparent electrode made of a copper wire mesh and the second one from a solid copper block. A maximum peak-to-peak alternating voltage of 3.8 kV was used for the modulation. The high resolution Ocean Optics (HR4000) spectrometer was used to obtain the room temperature photoluminescence (PL) spectra. The samples were

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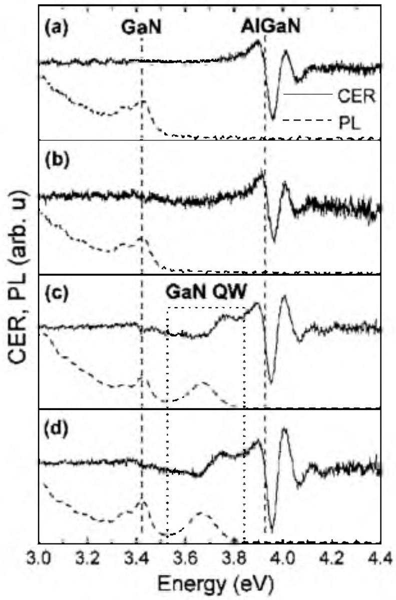

FIG. 1. Room temperature CER spectra (solid lines) and PL spectra (dashed lines) for (a) S1 $[Al_{0.27}Ga_{0.73}N(26.9\ nm)/GaN(2\ \mu m)]$, (b) S2 $[Al_{0.27}Ga_{0.73}N(26.7\ nm)/AlN(\sim 1.5\ nm)/GaN(2\ \mu m)]$, (c) S3 $[GaN:Si(2\ nm)/Al_{0.27}Ga_{0.73}N(26.7\ nm)/AlN(\sim 1.5\ nm)/GaN(2\ \mu m)]$, and (d) S4 $[GaN(2\ nm)/Al_{0.27}Ga_{0.73}N(26.7\ nm)/AlN(\sim 1.5\ nm)/GaN(2\ \mu m)]$ samples.

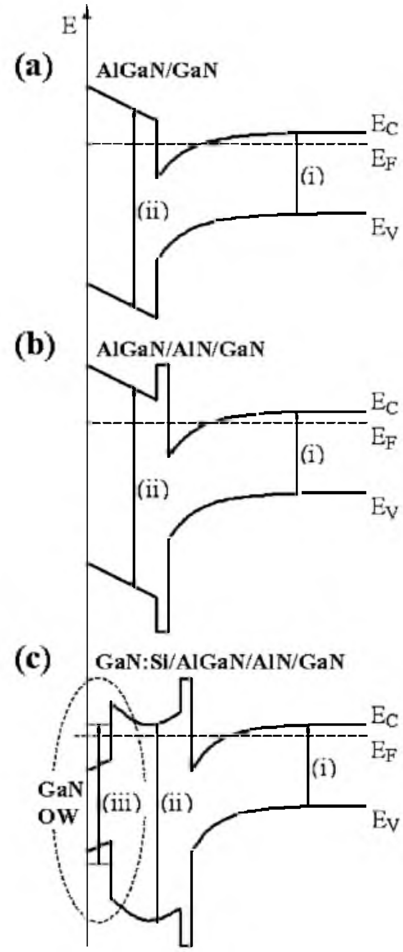

FIG. 2. Sketch of energy diagrams for (a) AlGaN/GaN heterostructure, (b) modified heterostructure with AlN interlayer, and (c) AlGaN/AlN/GaN heterostructures with a thin GaN:Si capping layer. The transitions labeled as (i) and (ii) are band-to-band absorptions in the GaN and AlGaN layers, respectively. The transition labeled as (iii) is an optical transition between the hole and electron states confined within the GaN surface QW.

excited with a 300 nm line of a Coherent Ar^+ ion laser. The laser spot diameter on the sample was ~0.5 mm and the pump power was less than 1 mW.

Figure 1 shows a comparison of CER and PL spectra for the four investigated structures. It is clearly visible that CER and PL spectra exhibit significant differences in the spectral region between the GaN and AlGaN band gap energies. These differences are directly attributed to the presence of GaN cap layer, as explained in the next part of this letter. In order to explain CER features, which are observed for the four samples, some sketches of the energy diagrams are shown in Fig. 2. The band bandings across the heterostructure results from the existence of large built-in spontaneous and piezoelectric polarization fields, which is typical for (Al,Ga)N systems and Fermi level pinning in *n*-type materials.

The CER spectrum of S1 sample [Fig. 1(a)] shows spectral features typical for AlGaN/GaN heterostructures.[18] Only one clearly visible CER resonance is observed at the energy of 3.96 eV. This resonance is attributed to the band-to-band transition in AlGaN layer [transition labeled as (ii) in Fig. 2(a)]. No signal associated with the GaN buffer layer is observed because of the screening phenomena of GaN buffer layer by the 2DEG.[18] This effect is also observed for the remaining heterostructures [see Figs. 1(b)–1(d)]. Note that the observation of screening phenomena in CER spectroscopy indicates that CER resonances observed below AlGaN band gap energy are associated with epilayers between the surface and the sheet of 2DEG. Note that in the case of photoreflectance spectroscopy, which is familiar to CER spectroscopy, the screening phenomena are not observed[18] and hence there is no proof that some spectral features observed below AlGaN band gap energy have to be associated with epilayers between the surface and the sheet of 2DEG. The screening effect in CER spectroscopy was discussed in detail in Refs. 18 and 19.

The CER spectrum of modified AlGaN/GaN heterostructure is presented in Fig. 1(b). The thin AlN layer, with a thickness of ~1.5 nm, was inserted between the AlGaN and GaN layers in order to improve the rf characteristics of a FET.[11,20] It is clearly visible that the CER spectrum for this sample is almost the same as for the unmodified AlGaN/GaN transistor heterostructure, i.e., only AlGaN-related resonance is visible. Some changes in CER spectra appear for AlGaN/GaN transistor heterostructures with the GaN cap layer.

Figures 1(c) and 1(d) show CER spectra for S3 and S4 heterostructures, respectively. Like in the case of the S1 and S2 heterostructures, a well visible CER resonance at the energy of 3.96 eV is observed in these spectra. As previously, this resonance is attributed to the AlGaN layer. Significant changes in CER spectra, in comparison to the S1 and S2 heterostructures, are observed within the energy range of ~3.6–3.75 eV. The modification of the AlGaN/GaN transistor heterostructure by adding of a thin GaN cap layer causes the formation of a surface GaN QW. In such a system, the confining potential is obtained from one side by the vacuum level, which is defined approximately by an electron affinity of ~2.7–4.1 eV, and from the other side by the band gap discontinuity between GaN and AlGaN (~0.82 eV[21]). Thus, the CER feature observed between ~3.6 and

~3.75 eV has been attributed to the optical transition between the hole and electron states which are confined in the surface GaN QW [see transition labeled as (iii) in Fig. 2(c)].

The optical transitions, which are associated with the surface GaN QW, were also investigated by PL spectroscopy, see Fig. 1. The two PL peaks at the energies of 3.35 and 3.42 eV and the broad PL band, which is observed below these peaks, are typical for GaN layers and, therefore, they are attributed to the GaN buffer layer. An additional peak appears at the energy of 3.67 eV for AlGaN/GaN heterostructures with the GaN cap layer. This peak is well correlated with the CER resonance, which is attributed to the surface GaN QW. The observed Stokes shift within the range of 30–80 meV together with a high broadening of the PL line (~120 meV) can be caused by several factors, which are discussed elsewhere. Finally, it has been concluded that the emission at 3.67 eV can be attributed to the surface GaN QW.

In conclusion, clear CER resonance between GaN and AlGaN band gap energies has been observed for AlGaN/GaN transistor heterostructures capped with ~2 nm GaN layer. This resonance has been attributed to the optical absorption between the hole and electron states which are confined within the surface GaN QW. The surface QW potential is obtained from one side by the vacuum level and from the other side by the band discontinuity between the GaN and AlGaN semiconductor materials. Also PL spectra have proven the existence of confined states within the surface GaN QW.

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