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Study of built-in electric field in active region of GaN/InGaN/AlGaNLEDs by electroreflectance spectroscopy

Lev P. Avakyants, Artem E. Aslanyan, Pavel Yu. Bokov *, Anatoly V. Chervyakov, Kirill Yu. Polozhentsev

Physics Department, M.V. Lomonosov Moscow State University, Leninskie Gory 1 b. 2, 119991 Moscow, Russia

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A B S T R A C T

Nitride-based heterostructures with InGaN/GaN multiple quantum wells in active region were investigated by electroreflectance spectroscopy. Two spectral lines with the stable difference between their phase parameters and slightly different energies were observed in the electroreflectance spectra under various bias voltages. Using models taking into account interference effects it was shown that electroreflectance signal at low amplitude of modulation voltage originates from the first and the last quantum wells in active region. The difference between built-in electric field strengths in these two quantum wells were estimated as 270–320 kV/cm.

1. Introduction

High-performance light sources in green, blue and ultraviolet spectral range, high temperature and high-frequency devices could be fabricate using nitride heterostructures [1]. InGaN/GaN quantum wells are used for manufacturing light emitting diodes (LEDs) in the blue and violet spectral range [2]. A strong piezoelectric field (up to MV/cm [3,4]) appears in the hexagonal InGaN quantum wells grown in [0001] direction due to the lattice mismatch between the InGaN well and the GaN barrier. Such strong built-in electric field modifies the band structure [5,6] and affects on the optical and electrical properties of the III-nitride heterostructures.

To improve the quantum efficiency of LEDs the multiple quantum wells (MQW) are placed into pn-junction. Nonuniform electric field in the pn-junction amounting with the piezoelectric fields leads to non-identical optical properties of each quantum well. As the matter of fact the increasing of quantum wells number by *N* times leads to improve LEDs efficiency less than *N* times. There are two main reasons of such behavior: overflow of quantum wells with carriers and increasing of the Auger-processes [7], and formation non-identical radiation conditions between quantum wells due to no uniform electric fields [8,9]. Thus, it is necessary to get a further insight into the piezoelectric fields in pn-junction in III-nitrides LEDs.

There are several modulation spectroscopy methods to explore an influence of electric fields on such systems. Contactless electroreflectance (CER) is used to study band bending, band gap bowing, Stokes shift [10], interband transitions, piezoelectric fields and the impact of indium concentration in QWs [11] on emitting properties of heterostructures based on InGaN/GaN layers. Recent study by means of photoreflectance (PR) with different temperatures and configurations of width, quantities of quantum wells and barriers shows the effect of incorporating In into barrier GaN layer [12] during the growth procedure.

Traditional ER spectroscopy allows to explore single group of layers more detail due to possibility of using of different regimes of modulation. Piezoelectric fields in MQW region of heterostructure based on GaN/AlGaN/InGaN previously were studied by ER spectroscopy. Two main effects were observed In ER spectra obtained at different bias voltages: interference fringes connected with the modulation of the refractive index [13], and signal, related to the interband transitions in the InGaN/GaN quantum wells [14].

In this work we present the results of analysis of ER spectra at low amplitude of modulation voltage. This regime allowed to obtain the ER signal from different quantum wells and estimate

* Corresponding author.
E-mail address: pavel_bokov@physics.msu.ru (P.Yu. Bokov).

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the difference between built-in electric fields strength in the quantum wells.

1. Samples and experimental technique

The sample under consideration was LED based on GaN/InGaN/AlGaN heterostructure. It was grown by metal–organic chemical vapor deposition (MOCVD) on sapphire substrate and flip-chip mounted by the p-side to the heat sink that works as a reflective mirror (Fig. 1). The area of the crystal was ≈0.4 mm^2. The buffer i-GaN layer had width <700 nm; an n-GaN layer of 4.5 μm; an InGaN/GaN buffer superlattice (20 periods, 2 nm quantum wells, 2 nm barriers), 5 quantum wells/barriers of $In_{0.12}Ga_{0.88}N$/GaN (active region with MQW), well width ≈4 nm, barrier width ≈4 nm; an electron blocking barrier of p-AlGaN of ≈20 nm, and p-GaN layer of ≈120 nm.

The ER spectra were registered by a 0.3 m double grating monochromator equipped with a Si photodiode in the spectral range of 2.3–3.2 eV [11]. The pitch angle of the probe beam was equal to 8°. A bias voltage (U_{dc} from 1.625 V to −1.125 V) and square wave modulation voltage U_{mod} (frequency of 370 Hz, amplitude from 0.125 V to 2.875 V) were applied on the pn-junction, so there are no carrier injection through the pn-junction. All experiments were carried out at room temperature.

2. Results and discussion

2.1. The estimation of the distance between quantum wells forming the ER spectrum

Fig. 2 shows the ER spectra from MQW region measured at different regimes of modulation. The spectra consist of superposition of ER signals from InGaN quantum wells in active region and can be resolved into two lines with energies of about 2.57 and 2.75 eV. Low-energy line has greater amplitude and a smaller width than the high-energy line. In addition all ER spectra show approximately constant phase parameters for each of these lines. To determine the parameters of spectral lines we used the sum of Aspnes's formulas [15]:

$$\frac{\Delta R}{R} = Re(A_1 \cdot e^{i\varphi_1} \cdot (E - E_{i1} + i\Gamma_1)^{-m}) + Re(A_2 \cdot e^{i\varphi_2} \cdot (E - E_{i2} + i\Gamma_2)^{-m}), \tag{1}$$

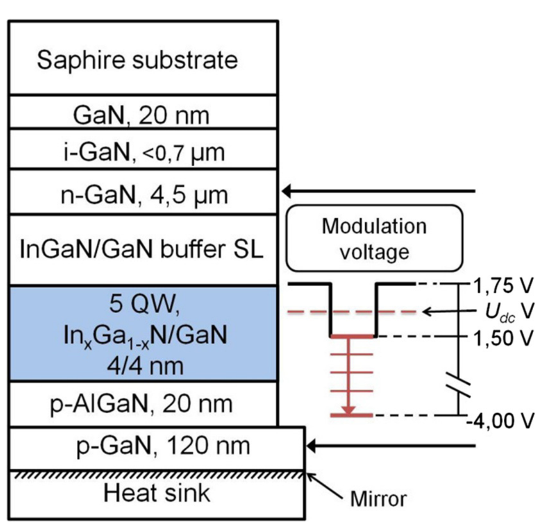

Fig. 1. Sample under investigation and modulation regimes.

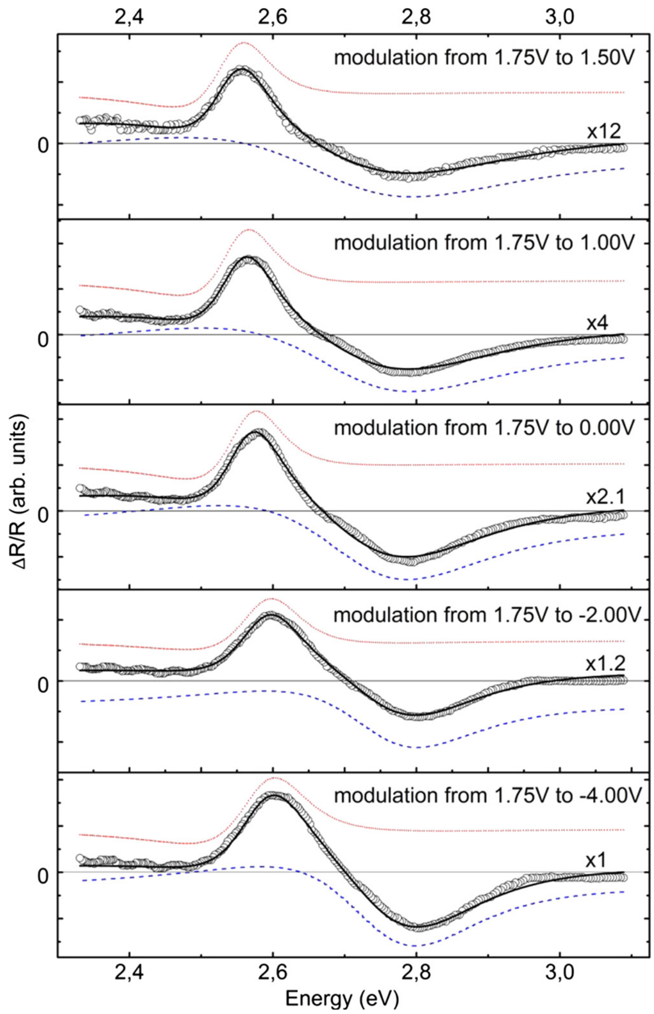

Fig. 2. ER spectra measured at different modulation regimes. Rounds – experimental data, dashed and doted lines are the example of fitting in accordance with Aspnes' model [15] and Eq. (1), solid line is the sum of dashed and doted one.

where A_1 and A_2 – amplitude parameters, φ_1 and φ_2 – phase parameters, $E = \hbar\omega$ – energy of reflected irradiation, E_{i1} and E_{i2} – transition energies of the first and the second lines, Γ_1 and Γ_2 – broadening parameters, m –dimension of critical point. We used $m = 2$, which is valid for excitonic transitions [16]. As it was shown by Klipstein [16], interference effects are strongly modified the ER spectra from MQW and the phase parameter of spectral line is connected with the interference of waves reflected from the surface and the quantum wells (Fig. 3). The difference of phase parameters of lines from quantum wells depends on their spatial position $L = L_2 - L_1$ (Fig. 3) relative to the surface [17]:

$$\Delta\varphi = \varphi_2 - \varphi_1 = 2 \cdot \frac{2\pi}{\lambda} \text{ Ln} \cos\theta, \tag{2}$$

where n – refractive index, θ – pitch angle, λ - wavelength. As the difference between phase parameters for all spectra is almost constant, we concluded that interference [15,17] occurs in wells, separated by layers with the quite defined thickness L (2).

As it follows from the fitting of all ER spectra registered at modulation voltage amplitude less than 0.875 V the difference between phase parameters $\Delta\varphi = \varphi_1 - \varphi_2$ equals 157° ± 5°. This difference was recalculated (2) into thickness L as (37.5 ± 1.2) nm. This value corresponds to interference between the first and the fifth quantum wells in the active region (see Fig. 1).