

# Photoconductivity of InGaN/GaN multiple quantum well heterostructures

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**Abstract.** Photocurrent and photoconductivity of InGaN/GaN multiple quantum well heterostructures as a function of applied reverse bias is investigated. Optical excitation was carried out in blue and violet regions of the spectrum, and temperature was ranging from 10 to 300 K. We observed characteristic features related to consequently moving space charge boundary through the quantum wells. For each quantum well there is a range of reverse bias with negative differential conductivity when excited by blue light. Frequency and temperature measurements revealed the presence of at least two different mechanisms that determine the photoconductivity of the structures.

## 1. Introduction

At the present time semiconductor heterostructures are widely used for the creation of electronic devices for various purposes. This was contributed by the significant progress made in recent years in the theory of such systems [1], and in growth technologies. The especial interest to InGaN/GaN multiple quantum well (MQW) structures is due to possibility of their use for light-emitting diode (LED) lighting. However, there are a number of obstacles to significant increase in the brightness of LEDs based on these structures. Among them there are reduction of efficiency as the injected current density increases (so-called efficiency droop), and non-uniform properties of the structure with depth, which prevents an increase in the intensity by increment of number of quantum wells in the active region. As a result at the present time much attention is paid to the problems of investigation and diagnostics of InGaN/GaN multiple quantum well structures. Today methods of admittance spectroscopy [2] and the capacitance-voltage (C-V) profiling [3] are widely used due to their high informational content. They can be utilized to determine the distribution of free charge carriers in the depth of heterostructure, *i.e.* obtain information about location and quality of each quantum well. A more informative method is admittance measurements, combined with optical excitation of heterostructure at a specific wavelength. If the photon energy is larger than band gap of the quantum well InGaN, but less than band gap of the barrier GaN, the absorption of light and the generation of excess carriers occur only in quantum wells. As a result, the response of each quantum well is increased. Thus, in [4], the method of capacitance-voltage profiling in combination with the optical excitation was used for determination of well-to-well non-uniformity in InGaN/GaN multiple quantum well structures.

In this work investigations of photoelectric phenomena in quantum well structures are described. The samples were commercial grade blue emitting LEDs based on InGaN/GaN MQW heterostructure. The photocurrent and differential photoconductivity as functions of reverse voltage applied to the *p-n*–



junction are investigated. The excitation was carried out by the light from LEDs emitting in blue and violet regions of the spectrum. We clearly observed characteristic features in photocurrent and photoconductivity related to consequently moving space charge boundary through the quantum wells.

## 2. Samples under investigation and experimental technique

The samples were commercial grade blue emitting InGaN/GaN LEDs. The wavelength at the maximum of luminescence was 465 nm. The area of  $p$ - $n$ -junction, measured using an optical microscope, was 0.067 mm<sup>2</sup>. From the capacitance-voltage measurements conducted with the modulation frequency of 1 MHz (Fig. 1a), it was determined that structures under investigation contained five quantum wells at a distance of approximately 18 nm from each other (Fig. 1b).

The measurements were performed on the automated setup [5], consisting of the helium cryostat Janis CCS-150/204N, the temperature controller LakeShore 325, the immittance meter E7-20, the power supply Agilent E3643A and a computer. Blue and violet LEDs were used as an exciting light source. The wavelength of the peak of luminescence spectrum for the blue LED was 465 nm and for the violet - 420 nm. The width of spectrum for both LEDs was about 30 nm, and the optical power was about 1 mW. The intensity of the optical excitation was constant, but was not normalized.

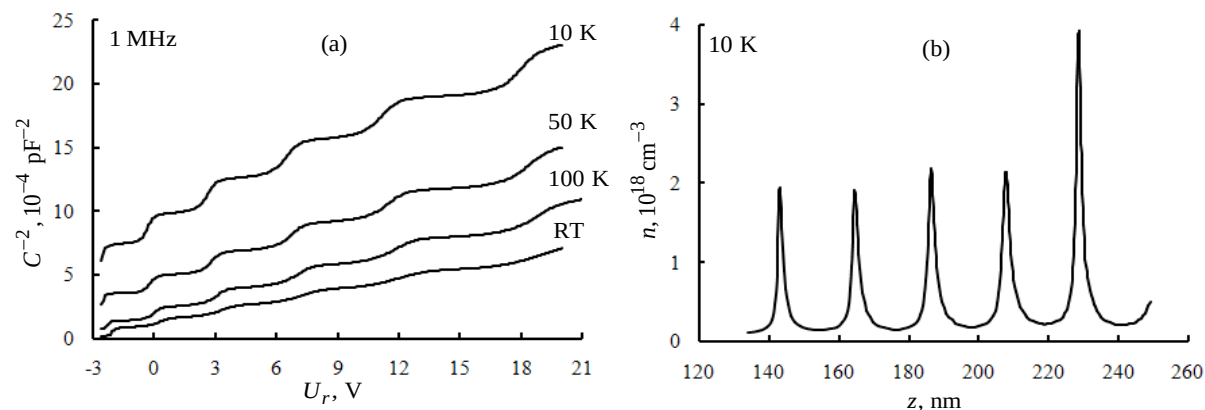


**Figure 1.** (a) – Capacitance of samples to the power of (-2) as a function of reverse voltage, measured at the frequency of 1 MHz at different temperatures; (b) – Charge carriers concentration profile, obtained by C-V-profiling at T=10 K.

Samples were measured as follows. The sample under investigation was held in a cryostat chamber and connected to the immittance meter, which allowed measuring electrical parameters of the sample such as the capacitance, the conductivity and the current. Temperature of the sample in the cryostat was ranging from 10 to 300 K. The excitation light was constantly focused on the sample through an optical window in the measuring chamber.

In measurements of photocurrent a constant voltage was applied to the samples, providing the bias of  $p$ - $n$ -junction, and the through current was recorded. Measurements were carried out under illumination and in the dark, after which the difference between them was obtained.

In measurements of differential photoconductivity a complex signal was applied to samples, which is the amount of DC voltage, providing the bias of  $p$ - $n$ -junction, and AC voltage with constant amplitude of 40 mV. Active and reactive components of admittance, the differential conductance and differential capacitance, were determined. Measurements of differential conductivity under illumination in the blue region of the spectrum and in the dark were conducted, after which the difference between them was obtained. Measurements were made at frequencies from 30 Hz to 10 kHz. The measurements were not made at higher frequencies, because there is a growth of dark conductivity as the frequency increases, against which the effects associated with the photoelectric phenomena become insignificant. This dark conductivity is associated with lagged recharge of deep

traps and bound states in the quantum wells when the external voltage is rapidly changing. In this work, this phenomenon is not discussed in detail.

### 3. Experimental data and discussion

The experimental investigation of the dependence of photocurrent in InGaN/GaN MQW heterostructures on the reverse bias revealed the presence of characteristic features. In Fig. 2 the photocurrent  $I_{ph}$  as a function of reverse bias  $U_r$  is plotted. These curves were obtained by optical excitation in violet (curve 1) and blue (curve 2) regions of the spectrum. A comparison of these curves with the data of capacitance-voltage measurements (dashed line in Fig. 2) suggests that the photocurrent features characterize the internal structure of samples. They occur at the voltages at which the boundary of the space charge region crosses the quantum wells. Indeed, in the case where the quantum well is in the quasi-neutrality area, where the electric field of the  $p$ - $n$ -junction is absent, the flows of charge carriers generated by light in all directions are the same, and the total photocurrent in this case is zero. Conversely, if the quantum well is located inside of the space charge region, the electric field of the  $p$ - $n$ -junction leading to efficient spatial separation of the light-generated electrons and holes, which have overcome the potential barrier of a quantum well by thermal emission. In this case the photocurrent is not zero. Thus, with increasing reverse bias, when the boundary of the space charge region crosses a quantum well, the photocurrent should rise sharply, as is observed in the experiment. Curve 1 in Fig. 2 clearly shows the stepwise increase of photocurrent.

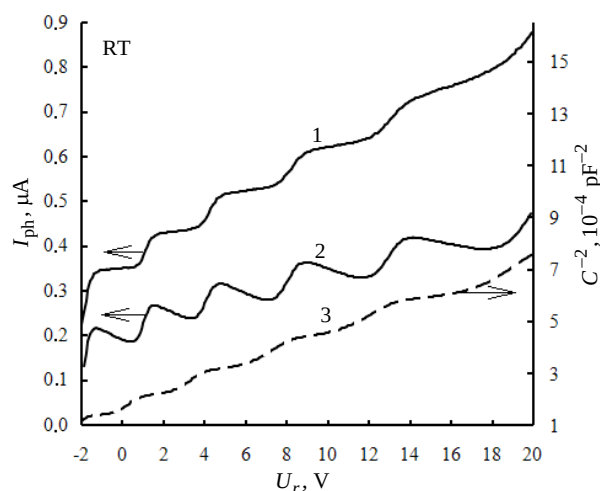


**Figure 2.** Photocurrent as a function of reverse voltage, measured with optical excitation in the violet (curve 1) and blue (curve 2) regions of the spectrum at room temperature. For comparison, on the second axis the capacitance-voltage dependence is plotted (dashed curve 3).

On the curve 2 there are areas of photocurrent decrease with increasing reverse bias. An essential condition for the emergence of this effect was that the optical excitation was carried out in the spectral region corresponding to the edge of the optical absorption of quantum wells InGaN. As described in [6], this effect is probably due to the decrease of the absorption of light as a result of the expansion of the space charge. At small reverse bias when InGaN quantum well is in the quasi-neutrality region, there is a strong built-in piezoelectric field inside the well. Due to quantum-confined Stark effect, the energy gap between the ground states of electrons and holes in a quantum well is much less than in the quantum well of the same width and depth, but without the piezoelectric field. With increasing reverse bias quantum well gets into the space charge region of  $p$ - $n$ -junction, the electric field is partially compensated piezoelectric field inside the quantum well. This results in an increase of the energy gap between the ground states of the electron and the hole, and the optical absorption edge is shifted to shorter wavelengths. As a result, the number of absorbed photons is significantly reduced.

In Fig. 3 the dependence of photocurrent on the reverse bias at different temperatures is plotted. It can be noted that the features of the photocurrent are most clearly observed at room temperature and at low temperatures they are significantly smoothed. This is due to the fact that charge carriers generated

by light in quantum wells, to participate in the photocurrent have to overcome the potential barrier of the quantum well. The most likely mechanism for this process is the thermal activation, so the increase in temperature leads to an increase in the photocurrent as well as enhancement of the features in the current-voltage dependence.

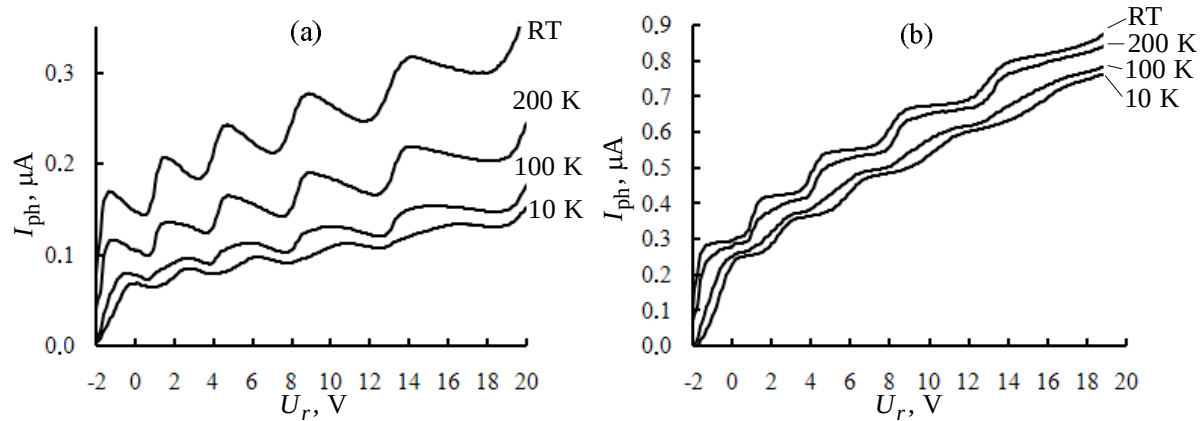


**Figure 3.** Photocurrent as a function of reverse voltage, measured under illumination in blue (a) and violet (b) regions of the spectrum at different temperatures.

More detailed information about the structure can give differential photoconductivity investigations at different frequencies and temperatures. Such studies allow the analysis of the rate of various mechanisms that determine the photoconductivity. In Fig. 4 a differential photoconductance vs. reverse bias is plotted. Fig. 4a shows the data obtained at a frequency of 300 Hz at different temperatures. Fig. 4b shows the dependencies obtained at different frequencies at 150 K. The sharp peaks in the conductance at reverse voltages 1.1, 4.2, 8.3, 13.2 and 20 V related to abrupt increases in the photocurrent when the boundary of the space charge crosses quantum wells. The amplitude of the peaks decreases with decreasing temperature and is almost independent of frequency.

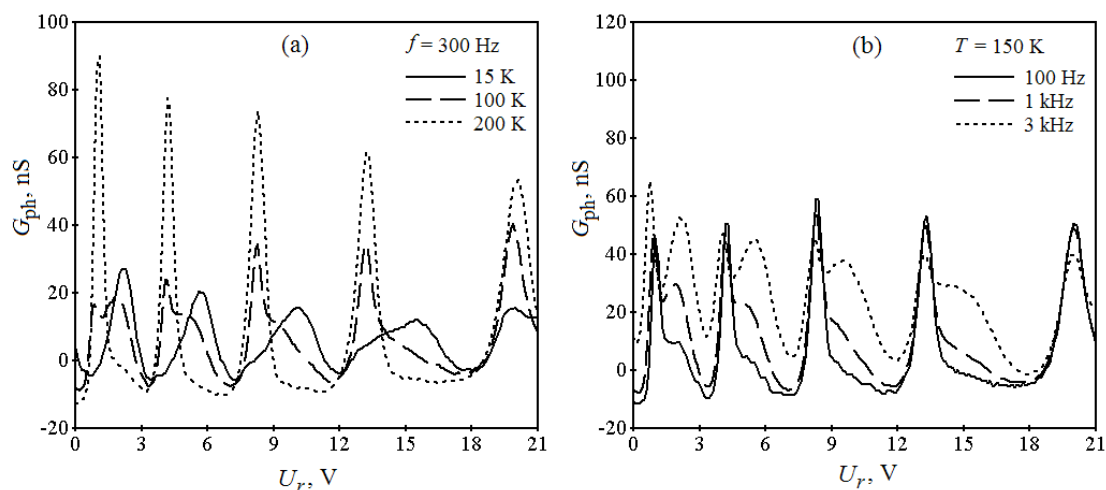


**Figure 4.** Differential photoconductance as a function of reverse voltage.

This behavior is indicative of the fact that the photoconductivity depends on the process of thermal emission of carriers from quantum wells into the barriers. For each quantum well, there is also an additional peak observed at higher voltages than the first peak. Additional peak exists only at low temperatures, and its amplitude increases with decreasing temperature and increasing frequency. The origin of this phenomenon is not explained. These data suggest that the formation of the photocurrent

is probably attended by several competing mechanisms at different rate; their probabilities depend on temperature and frequency.

#### 4. Conclusion

The investigation of InGaN/GaN multiple quantum well heterostructures have shown that the dependence of photocurrent on the reverse bias characterize the internal structure of the samples. At voltages when the boundary of  $p$ - $n$ -junction space charge crosses quantum wells, the photocurrent sharply increases, that is related to spatial separation of the light-generated charge carriers in the electric field of the  $p$ - $n$ -junction. It is experimentally shown that when the optical excitation is carried out at a wavelength close to the absorption edge in quantum wells, there are areas of negative differential conductivity. It is assumed that their presence is associated with the shift of the optical absorption edge in quantum wells to the shortwave region, caused by compensation of piezoelectric field in the quantum wells by the electric field the  $p$ - $n$ -junction. In the case of excitation by light with high energy photons negative differential conductivity disappears.

It is experimentally shown that features of the photocurrent are most pronounced at room temperature and are significantly smoothed at low temperatures. It is explained by the fact that for participation in photocurrent the charge carriers must overcome the potential barrier of the quantum well. The mechanism of this process is the thermal activation, the probability of which is maximal at high temperatures. However, investigations of the differential photoconductivity at different frequencies and temperatures revealed the presence at least one another mechanism that influences the photoconductivity. It is more probable at low temperatures and high frequencies. The origin of this phenomenon is not explained.

Based on these results, we can conclude that the research of dependence of photocurrent on the reverse bias can be used as an effective non-destructive method for diagnostics of semiconductor heterostructures [7], in particular, LEDs based on InGaN/GaN MQW structure. There are several advantages of this approach in relation to commonly used admittance methods. Firstly, the implementation of this method requires relatively simple equipment: a voltage source, a current meter and a source of optical excitation, *e.g.* LED or laser. Secondly, the measurements of a sample can be made for hundredths of a second. It can be achieved because the instantaneous value of current is measured. Unlike this, for the capacitance measurements the lock-in amplifiers are used. Finally, the observed features in photocurrent associated with quantum wells are most pronounced at high temperatures, so the cryostat is not required for the measurements.

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