ELECTRONIC AND OPTICAL PROPERTIES OF SEMICONDUCTORS

Low-Temperature Time-Resolved Photoluminescence in InGaN/GaN Quantum Wells


Ioffe Physicotechnical Institute, Russian Academy of Sciences,
Politekhnicheskaya ul. 26, St. Petersburg, 194021 Russia

Submitted December 6, 2001; accepted for publication December 18, 2001

Abstract—The results of the investigation of low-temperature time-resolved photoluminescence in undoped and Si-doped In$_{0.2}$Ga$_{0.8}$/GaN structures, which contain 12 quantum wells of width 60 Å separated by barriers of width 60 Å, are reported. The structures were grown by the MOCVD technique on sapphire substrates. The photoluminescence properties observed are explained by the manifestation of two-dimensional donor–acceptor recombination. These properties are the high-energy shift of the peak upon increasing the pumping intensity, a low-energy shift with increasing delay time, and a power law of luminescence decay of the $r^{-3}$ type. The estimates of the total binding energy for donor and acceptor centers are given. This energy is 340 and 250 meV for Si-doped and undoped quantum wells, respectively. The role of the mosaic structure, which is typical for Group III hexagonal nitrides, is discussed as a factor favorable for the formation of donor–acceptor pairs.

1. INTRODUCTION

At present, heterostructures and structures with quantum wells (QWs) based on InGaN/GaN systems are being intensively investigated. This is associated with the necessity of increasing the operating life of ultraviolet lasers and of extending the spectral range of semiconductor lasers [1, 2]. This is also associated with the application of these structures in the new generation of semiconductor electronic devices, which can operate at high temperatures [3].

Optical properties and, specifically, photoluminescence (PL) and electroluminescence of the structures with In$_{x}$Ga$_{1-x}$/N/GaN QWs have been investigated in many studies [4–16]. In some publications [8, 10], the luminescence in InGaN/GaN QWs was attributed to recombination of dimensionally quantized electrons and holes, which are strongly affected by the built-in piezoelectric field. This field emerges due to the distortion of the QW material. On the other hand, it was also reported that a piezoelectric field really exists in the structures with single QWs and is actually absent in the structures with multiple QWs, due to the stress relaxation [11, 12]. The model of recombination of excitons localized on the fluctuations of the solid solution is also used to explain the effective luminescence of the InGaN/GaN QWs [13–16]. According to this model, the fluctuations of In content give rise to potential wells for excitons or even quantum dots in the QW plane. These objects trap the excitons and act as the effective centers of radiative recombination. However, the entire set of known experimental data on the luminescence properties in the InGaN/GaN QWs cannot be explained completely in the context of any of these models. Moreover, it is possible in some cases to encounter contradictions within one or another model used for the discussion even of a small group of experimental data. By virtue of this fact, further investigations and the establishment of the mechanisms responsible for spontaneous emission in actual device structures are urgently needed.

In this paper, we present the results of the investigation of time-resolved PL in structures with multiple InGaN/GaN QWs, both Si-doped and without special doping, which were formed by the MOCVD method on sapphire substrates.

2. EXPERIMENTAL

The structures were formed by the low-pressure MOCVD method on Al$_2$O$_3$(0001) substrates and contained a GaN layer 2.5 μm thick; an In$_{0.1}$Ga$_{0.9}$N layer 250 Å thick; 12 In$_{0.2}$Ga$_{0.8}$/N/GaN QWs 60 Å thick, with barrier widths being also 60 Å thick; and then a GaN layer 0.1 μm thick. The results of the transmission electron microscopy investigation of the structures obtained are indicative of the high quality of the InGaN/GaN interfaces. The details associated with producing the structures were described previously [17]. Two types of structures were investigated, namely, Si doped to the level of $\approx 10^{18}$ cm$^{-3}$ and nominally undoped Si.

Photoluminescence was excited by the radiation of a pulsed nitrogen laser ($\lambda_{exc} = 337$ nm), which operated at a frequency of 400 Hz with a pulse duration of 6 ns. The level of optical excitation varied within the range...
from 0.6 to $4 \times 10^4$ W/cm$^2$, which was achieved using calibrated neutral filters. The photoluminescence was measured using a DFS-24 double diffraction monochromator and a FEU-100 photomultiplier, which possesses a high sensitivity and a relatively uniform spectral sensitivity in violet and ultraviolet spectral regions. The time-resolved PL spectra and kinetics of the emission decay were obtained using a measuring system based on a BCI-290 boxcar integrator linked to a computer. The total time resolution of the recording system was approximately 10 ns. The experiments were carried out mainly at the liquid-helium temperature (4.2 K). However, certain reference experiments were also carried out at $T = 78$ and 300 K.

3. RESULTS AND DISCUSSION

With low-intensity pumping (0.6 W/cm$^2$), the QW emission spectrum measured at the peak of the laser pulse (Fig. 1a) is represented by a band with a peak at 2.784 eV and a half-width of $\approx 83$ meV. The low-frequency shoulder in the emission spectrum is probably determined by the phonon replica of the fundamental line at 2.784 eV. A small shift (no larger than 30 meV in the pumping range from 0.6 to $4 \times 10^4$ W/cm$^2$) of the PL band peak to the short-wavelength region can be seen with increasing photoexcitation intensity. A certain broadening of the PL band is also observed with an increase in the pumping intensity. This pattern, with variations of the PL spectrum with increasing excitation intensity, is illustrated in Fig. 1b.

The “violet” shift of the luminescence spectrum of InGaN/GaN QWs with an increase in the pumping intensity was observed in a large number of studies. One of the possible causes of this behavior is the screening of the built-in piezoelectric field by nonequilibrium charge carriers, which are generated as a result of optical excitation [8, 9, 18]. Actually, such screening should lead to the suppression of the dimensional Stark effect in the QW, which should cause a shift of the PL band to higher energies and a narrowing of this band as observed, e.g., in the case of isolated GaAs/AlGaAs QWs [19]. In the experiment with the structures which contain numerous InGaN/GaN QWs, the emission band is broadened with increasing excitation intensity (Fig. 1). Another explanation of the high-energy shift of the emission spectrum with an increase in pumping intensity is based on the effect of filling the localized tail states with nonequilibrium charge carriers [20, 21].

The recombination of excitons localized at compositional fluctuations of the solid solution was considered as the cause of the effective PL in the InGaN/GaN QWs [13, 14]. However, in the context of this model, it is rather difficult to explain the variations observed in the emission spectra at relatively low photoexcitation intensities ($\approx 10^2$ W/cm$^2$). The model of localized excitons is believed to be validated by the characteristic dependence of PL decay on the emission energy [14, 22]. This dependence is qualitatively similar to the dependence observed in the case of recombination of localized excitons in II–VI solid solutions [23]. The approach for the analysis of transient PL properties, which is similar to that used in studies [14, 22], for the InGaN/GaN QWs investigated in this study yields a radiative lifetime of localized excitons of about 60–70 ns, which seems to be unrealistic. These factors give no way of assigning the PL observed to the recombination of localized excitons. On the other hand, the shift of the PL peak to higher energies with an increase in pumping intensity can be associated with the manifestation of the recombination of donor–acceptor pairs. Two causes of the shift of emission bands of donor–acceptor pairs to higher energies with increasing photoexcitation intensity are possible. First, in the case of steady-state photoexcitation, the role of close pairs in the donor–acceptor recombination increases with an increase in the pumping intensity (see, e.g., [24, 25]). Second, nonequilibrium charge carriers can smooth the random potential relief, which, in its turn, is caused by a high