Functional Materials 19, No.2 (2012)

Luminescence of nanostructures based on semiconductor nitrides

E.A.Menkovich, S.A.Tarasov, I.A.Lamkin

St. Petersburg Electrotechnical University "LETI" (ETU),
5 Prof. Popova Str., 197376 St.Petersburg, Russia

Received March 9, 2012

Light-emitting diode structures on the basis of (Al, Ga, In)N solid solutions with and without superlattices were investigated. Experiments in a wide range of temperatures (10–300 K) and noise currents (10 nA – 2 mA) were performed. It was found that the structure with superlattices has a higher stability and better work performance. Apparently, the use of superlattices can compensate for the elastic stresses and piezoelectric fields at the heterointerface. This compensation reduces the formation of dislocations in the structures with superlattices, which increases the intensity of radiation and decreases self-heating effects.

Исследованы высокоэффективные светоизлучающие диоды с добавлением и без добавления сверхрешетки на основе твердых растворов (Al, Ga, In)N. Исследования проведены в широком диапазоне температур (10 -300 К) и шумовых токов (10 нА - 2 мА). Установлено, что структуры с добавлением сверхрешетки обладают более высокой стабильностью работы и лучшими рабочими характеристиками. Сделано предположение, что использование сверхрешетки компенсирует упругие напряжения и пьезополя на гетерогранице. Такая компенсация напряжения уменьшает образование дислокаций в структуре с добавлением сверхрешетки, что увеличивает интенсивность излучения и уменьшает эффект саморазогрева.

1. Introduction

The modern level of nanoheterostructure technology based on solid solutions of semiconductor nitrides allows creating bright and highly efficient light-emitting diodes (LEDs). In the future, they will be applied not only as signal elements for indicator devices, but also as basis for energy-efficient, environmentally friendly and cost-effective lighting. At the moment, efficiency of the best LED is more than 180 lm/watt. This is not only much higher than the efficiency of traditional incandescent bulbs, but also 2 times higher than the light conversion efficiency of fluorescent lamps. Nevertheless, the achieved values of white LEDs' efficiency are still significantly below the theoretical limit that is close to 100 %. Therefore, work is currently underway to optimize their designs for further improve energy conversion efficiency, reliability of their work, and reducing their costs.

It is known that the internal quantum efficiency of nitride short-wave LEDs is confined by the elastic stresses at the interface and defects in the active region of the structure. Various technological methods are being developed to reduce these stresses and defects. Quantum wells are created in the emitting crystals of LEDs, which greatly increase their luminescence efficiency and temperature stability of the power characteristics. One option is to use a short-period InGaN/GaN superlattice [1-3]. In particular, such superlattice can increase the efficiency of carrier injection into a quantum well located at a large distance from the *p*-doped region [3]. Significant reduction in defectiveness of the structure is achieved by adding to the crystal the super-

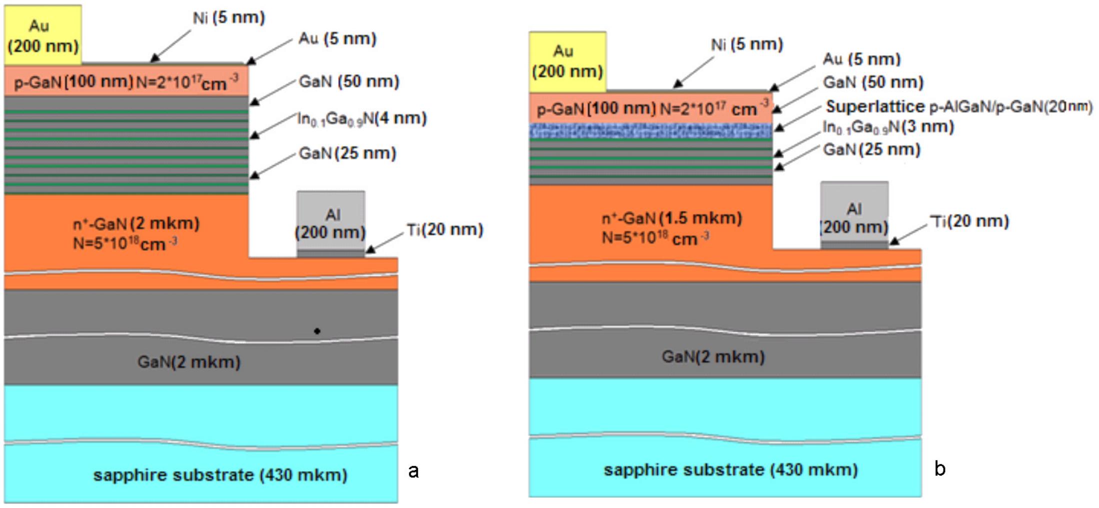

Fig. 1. The tested LEDs: type A (a) and type B (b).

lattice, consisting of alternating layers of undoped AlGaN and highly doped AlGaN: Si [5], or of a composition of AlN/AlGaN [6] layers. Below, it will be shown that the proposed version of the AlGaN/GaN superlattice will made it possible to reduce the amount of elastic stresses in the active region, thus diminishing the formation of dislocations in the structure, increasing the intensity of radiation and reducing self-heating effects.

2. Experimental

We investigated luminescence emitting from nanoheterostructures made on the basis of (Al, Ga, In)N solid solutions. The experiment was conducted in a wide range of temperatures (10 – 300 K) and currents (10 nA – 2 mA).

The investigated semiconductor crystals (Fig. 1) were created by MOCVD. They have been grown on 450 mm thick sapphire substrates. GaN buffer layers of 2 mm thickness have been grown to protect the active region from defects arising due to the mismatch between the lattice constant of sapphire and the semiconductor. Then 2 mm thick n^+-GaN layer was created, which acts as the lower contact to the structure. The LED's active region contains a set of 5–10 InGaN quantum wells of 4–5 nm width. The wells were separated by GaN barriers with thickness ranging from 25 to 50 nm. A further 100 nm thick p-GaN layer was grown with the dopant concentration about 10^{17} cm^{-3}. Some of the LED nanoheterostructures contained AlGaN/GaN superlattices with a period of 20 nm between the top p-GaN layer and the active region. For convenience, we would refer to the crystals that contain superlattice of type A, and those of type B. Ohmic contacts to p-type regions were created by aluminum deposition with a 20 nm thick titanium sublayer, and to n-type regions by gold deposition. Thin layers of nickel and gold were deposited on the emitting area for a better current spreading.

The experiment employed a measuring facility contained closed-cycle helium cryostat Janis CCS-150, and optical devices from Ocean Optics (FOIS-1 Fiber Optic Integrating Sphere, USB4000 Fiber Optic Spectrometer, HR4000 High-resolution Spectrometer, and the reference lamp LS-1 Tungsten Halogen Light Source). Specially designed LabVIEW program makes it possible to automate the measurements. The experiment was carried out in accordance with international standard CIE 127:2007. This allowed to increase the accuracy of the luminescence spectra analysis.

Closed-cycle cryostat Janis CCS-150 allowed conducting experiments in the 10–325 K temperature range. The temperature was controlled by Lake Shore-325 controller. Miniature fiber-optic, quick scan spectrometers USB4000 and HR4000 provided the experiments in the 350–1100 nm range. Reference lamp LS-1 Tungsten Halogen Light Source was used to calibrate the spectrometers' sensitivity. This has made it possible to measure the power of nanoheterostructures fluorescent radiation.

3. Results and discussion

The experiments results demonstrated an influence of forward current change on the luminescence spectrum at different ambient

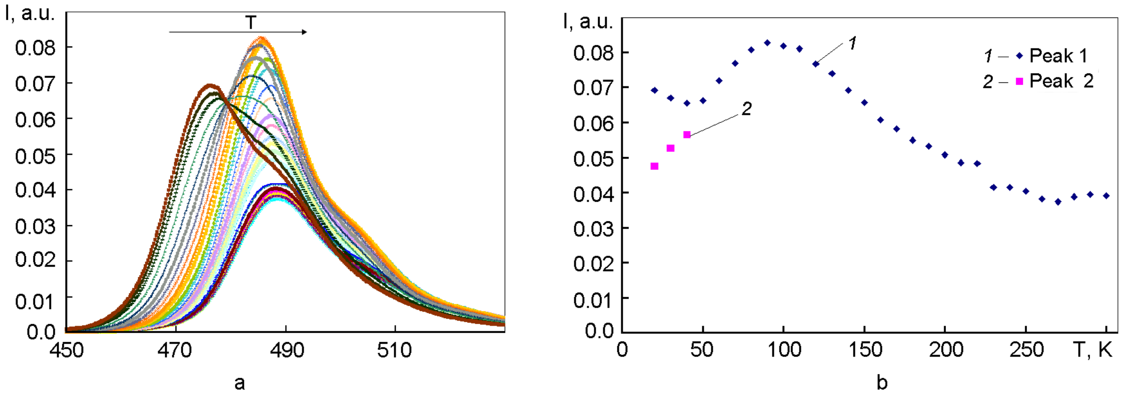

Fig. 2. The temperature dependences: of the emision intensity (a) and of the peak emission intensity (b).

temperatures. The radiation peak wavelength has not only been found to shift thermally, but also to exhibit abrupt shifts to different wavelength, which may indicate the change of working levels in the quantum wells. Experimental data analysis will be focused on the comparison of type A and B structures and on the superlattice influence study.

Change of the luminescence spectrum of structure type A at the ambient temperatures of 10–300 K is considered in Fig. 2. The spectral analysis reveals some important effects. The temperature decrease leads to a shift of the luminescence spectrum towards short wavelengths. This effect is a consequence of the semiconductor band gap increase. Also, there is an increase of luminescence intensity due to a decrease in the number of phonons in the crystal and an increase of the luminescence efficiency. However, the increase in luminescence intensity at the working wavelength suddenly gives way to a fall at the temperature of 100 K (Fig. 2b). An additional short-wave maximum has appeared at the wavelength of 475 nm when the LEDs were further cooled. The luminescence intensity increases and the maximum becomes dominant at a temperature of 50 K. The long-wavelength maximum continues to decline and it can only be seen as an inflection on the luminescence spectrum.

The observed effect is most likely associated with a change in the probability of optical transitions between size-quantization levels at lower temperatures. From a physical point of view, the effect may be attributed to the increasing difficulty of charge carriers' thermalization process in the quantum wells. In this case, they are retained in the higher levels and optical transition takes place from these levels. The delay effect increases at lower temperatures. Another factor influencing the change of intensity transitions is the presence of elastic stresses on the boundary and a piezoelectric field in the quantum wells. This factor becomes more noticeable with temperature decrease. However, based on the analysis of the experimental data, we can conclude that the main influence in this case is attributed to the first factor, since the above effect is very clearly observed in samples with superlattice.

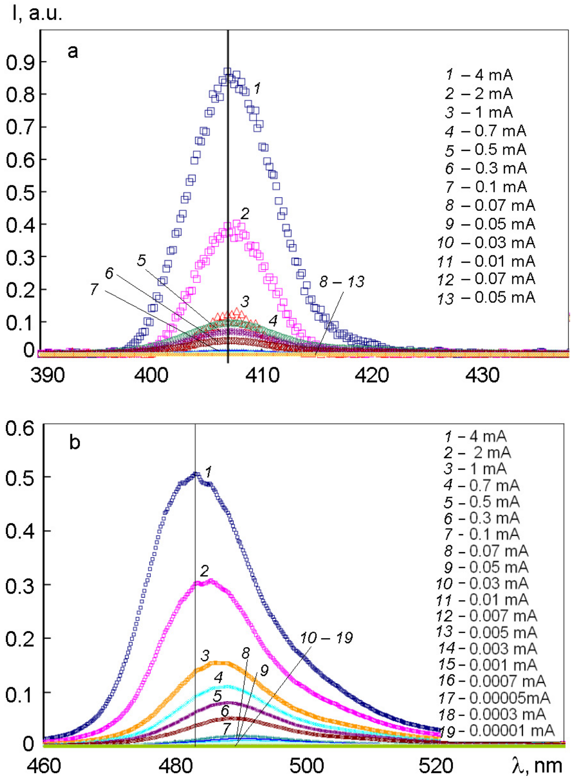

Fig. 3. The operating current dependence of the emission intensity for LEDs of type A (a) and type B (b).

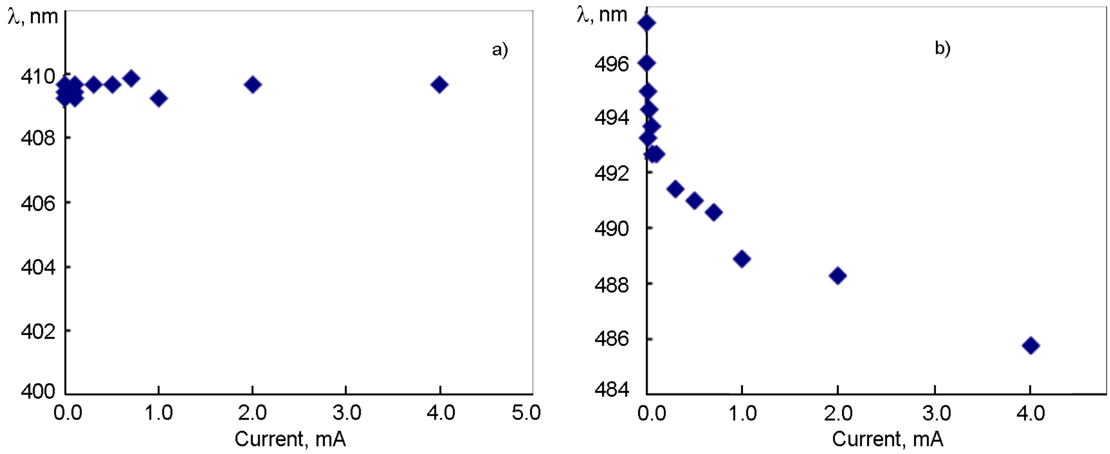

Fig. 4. The dependence of the peak wavelength of the radiation spectrum the operating current for LEDs of type A (a) and type B (b).

In our opinion, the most pronounced effect of the elastic stresses was shown in the study of nanoheterostructures luminescence spectra at very small forward currents. In order to study this effect a series of measurements was made with the value of the transmitted current lowered to a level of 10 nA. The Fig. 3 shows the luminescence spectra of structures A and B, obtained by applying low currents. Self-heating of the structure can be neglected in this case. There is significant difference in the spectra behavior for different types of structures. The dominant wavelength of the superlattice structure has remained unchanged. At the same time, the wavelength shift was very strong for type B structures. This is illustrated in Fig. 4. The wavelength shift for type B structures exceeded 10 nm, and came towards longer wavelengths. The nanoheterostructures based on semiconductor nitride quantum wells may exhibit a peak shift towards shorter wavelengths with an increase of forward current due to filling of higher levels in the density of states tails. However, this effect is not very large and can not explain such a dramatic shift of the spectrum. Most likely, in our samples this effect manifests itself at currents greater than 1 mA.

We believe that the luminescence spectrum shift at low currents in the type B structures is conditioned by the influence of elastic stresses and piezoelectric fields at the heterointerfaces. Influence of piezoelectric field is strongly noticeable when external voltage is low. Therefore, the form of the well is greatly distorted under piezoelectric influence, which leads to a significant reduction in distance between the working levels. Piezoelectric field is compensated with the increase in external voltage, and the wavelength is decreased.

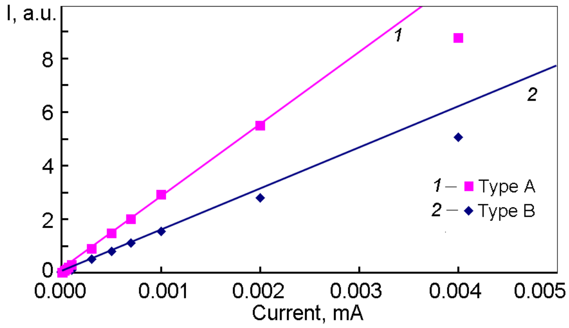

Fig. 5. The dependences of the peak emission intensity on the operating current for LEDs of type A (*1*) and type B (*2*).

Superlattice nanoheterostructures do not demonstrate any shift of maximum spectra wavelength (Fig. 4b). We believe this is due to a compensation of elastic stresses by the superlattices. This is explained as follows. Quantum wells were made on the basis of InGaN solid solutions. The lattice constant inside the wells is larger than one of gallium nitride barriers. Superlattices were made on the basis of AlGaN solid solution. Its constant is less than one of the gallium nitride. As a result, the stretching and lattice compression compensate each other. Thus, the type A structure shows a significantly higher stability of the radiation wavelength.

Elastic stresses will relax during the LED operation with the formation of qdislocation defects in the active region. The stresses compensation that was produced by superlattice should reduce the formation of dislocations in the type A structure. Therefore, this structure may have the best operating parameters. Experiments have confirmed this assumption (Fig. 5). The luminescence intensity of the superlattice structures is significantly higher than one for the type B. In addition, deviation from linearity begins in the type A crystals at higher currents. This indicates a lower self-heating effect, which is in turn caused by a lower concentration of the defects. Thus, the superlattice structure can create brighter light-emitting diodes.

4. Conclusions

We investigated the luminescence of emitting nanoheterostructures made on the basis of (Al, Ga, In)N solid solutions. Some of them contained superlattice between the top *p*-GaN layer and the active region. These samples were named type A and type B. Experiments were conducted in a wide range of extreme temperatures (10 – 300 K) and forward currents (10 nA – 2 mA). The experimental data analysis was focused on the comparison of type A and B structures and on the superlattice influence study. The experiments allowed studying the luminescence spectrum change dependent on the forward current at different ambient temperatures (300 K – 10 K). At these circumstances, there was not only the thermal shift of peak wavelength radiation, but also an abrupt shift of the maximum emission wavelength, which may indicate a change of the working levels in the quantum well. The observed effect is most likely associated with a change in the probability of optical transitions between quantum well levels at lower temperatures. In addition, it was found that the type A structure has a higher stability and better work performance. We believe that this is due to the following. Apparently, use of superlattices compensates elastic stresses and piezoelectric fields at the heterointerface. This compensation reduces the formation of dislocations in the type A structure, which increases the intensity of radiation and decreases self-heating effects.

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Люмінесценція наноструктур на основі напівпровідникових нітридов

Е.А. Менькович, С.А. Тарасов, І.А. Ламкін

Досліджено високоефективні світловипромінювальні діоди з додаванням і без додавання надгратки на основі твердих розчинів (Al, Ga, In)N. Дослідження проведено у широкому діапазоні температур (10-300 К) і шумових струмів (10 нА - 2 мА). Встановлено, що структури з додаванням надгратки володіють вищою стабільністю роботи і кращими робочими характеристиками. Зроблено припущення, що використання надгратки компенсує пружну напругу і п'єзо ополя на гетеромежі. Така компенсація напруги зменшує утворення дислокацій у структурі з додаванням надгратки, що збільшує інтенсивність випромінювання і зменшує ефект саморозігрівання.