The application of the Methods of Cathodoluminescence and Photoluminescence for Non-destructive Testing of AlGaN Heterostructures

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Abstract. This paper examines cathodoluminescence spectra of samples on sapphire substrates to develop methods of non-destructive testing of wafers with AlGaN/GaN heterostructures. It has been determined that the cathodoluminescence peak of AlGaN compound was demonstrated for decreased energy of excitation electrons (at 0.5 eV and 1 keV) only. Cathodoluminescence peak of AlN compound with energy of 6.15 eV was demonstrated at any excitation energy of 0.5 to 6.15 eV. It has been demonstrated that cathodoluminescence spectrum analysis allowed determining aluminum percentage in AlGaN, which was essential for inward testing of wafers for microwave transistors production. Data on the intensity distribution of "yellow" photoluminescence over the wafer surface has been obtained, and it has been demonstrated that these measurements were a prospective method of non-destructive testing to sorting wafers by defects.

1. Introduction
There are a number of publications which state that in order to obtain high-quality AlGaN/GaN-based high electron mobility transistors, Al content in the AlGaN layer should be within the range of 20 to 35%. The main purpose of this work is to develop cathodoluminescence methods as implements for non-destructive testing in order to determine aluminum content in heterostructures before their production is started. Methods of cathodoluminescence and photoluminescence are effectively used for examination of properties of wide-band gap materials and structures, in particular, for examination of dislocation nature in GaN thin films and for control of self-radiation related to a band-to-band junction [1–3]. Cathodoluminescence and photoluminescence allow detecting the defects related to luminescence in the visible spectrum. The relation between the so-called "yellow" cathodoluminescence excited by electrons of various energy and resistance of ohmic contacts of a GaN source and drain of microwave transistors has been ascertained. Aluminum content in AlGaN layers has been examined, in particular, in the work [3], however, thick layers of specified material (hundreds of nanometers thick) have been used. In this work, AlGaN layers with a thickness of 20nm have been examined.
2. Examination of Cathodoluminescence

JSM7001F scanning electronic microscope (JEOL, Japan) has been used for the purpose of the examination. Electronic microscopic images have been obtained in secondary electrons for electron energy of 15 keV. INCA Energy 350XT add-on device (Oxford Instruments Analytical, UK) has been used for the purpose of performing X-ray fluorescent analysis. Thus, peak x-ray characteristic radiation of film elements has been analyzed. MonoCL3+ add-on device for spectral analysis of cathodoluminescence (Gatan, USA) has been used for the purpose of the cathodoluminescent examination. The light induced in near surface layers of the sample affected by energetic electrons has been collected with parabolic mirror and directed to the input slot of a monochromator equipped with rotary diffraction grating. Cooled photoelectronic multiplier has been used as a light receiver. Spectral range of the spectrometer is 190 to 1100 nm. Spectra obtained have not been adjusted to the spectrometer's performance. 1200 grooves/mm diffraction grating with maximum shining at a wavelength of 500 nm has been used to record reviewed (within the range of 190 to 800 nm) spectra of GaN/AlGaN structures; 1200 grooves/mm diffraction grating with maximum shining at a wavelength of 250 nm is used to record UV range spectra. The sample has been cooled down to 80 K temperature, but most of the spectra have been recorded at room temperature. Spectral resolution has been 1nm. It has been established that most informative were the cathodoluminescence spectra measured for electron energy of 5, 3, 2, 1 and 0.5 keV. Figure 1 illustrates the graphical representation of the excitation area depth for such energies.

![Figure 1. Assessment of the energy loss per length unit depending on the penetration distance of electrons for various energy of electrons (Monte-Carlo simulation).](image)

The structures examined in our work are the following (as from surface): i-GaN (1.5 nm), i-AlGaN (20 nm), i-GaN (2300 nm), nucleation layer (thickness is not specified), sapphire. According to the manufacturer's data, Al content in structure of Al$_{x}$Ga$_{1-x}$N$_{x}$ = 0.3.

Figure 2 and Figure 3 illustrate the graphical representation of the cathodoluminescence spectra for various energy of electrons exciting cathodoluminescence. Figure 2A and Figure 3a clearly illustrate the highest peak of cathodoluminescence related to GaN excitons (3.42 keV).

The peak with energy of 6.15 eV is demonstrated for all energies of exciting electrons, which is approximately corresponding to the forbidden band of AlN. Nevertheless, location of the AlN layer is not clear, and the manufacturer has not mentioned this layer. Furthermore, there is no peak related to the AlGaN layer for exciting electron energy of 3 keV. There are no such peaks for higher energy of electrons exciting cathodoluminescence up to 15 keV. In addition, the cathodoluminescence peak with energy of 5.12 eV is indicated for all energies of exciting electrons. Unfortunately, this peak is hard to identify, possibly, it is related to junctions in the forbidden band of the AlN wide-band material.
The dependence of the maximum position of the exciton photoluminescence peak for triple compound Al\(_x\)Ga\(_{1-x}\)N on x (atomic fraction of Al) has been determined by experiment in the work [3, 4]. In this case, the cathodoluminescence peak with energy of 3.97 eV has been demonstrated for energy of exciting electrons of 0.5 eV (and for energy of 1 keV) which corresponded to aluminum content of x = 0.24. It should be noted that, the maximum value of "yellow" cathodoluminescence for decreased energy or exciting electrons is very clearly indicated in Figure 2A.

### 3. Examination of Photoluminescence

Photoluminescence, which was excited by ultraviolet LEDs with a wavelength of 295 nm, has been measured on the same samples on which cathodoluminescence has been measured in addition to the examination of cathodoluminescence. The purpose of this work was to obtain a new data on defects in GaN-based structures by photoluminescence methods and develop examination methods and method of inward express-testing of wafers with heterostructures before starting their production. Photoluminescence has been used to make the "maps" of "yellow" photoluminescence over the area of AlGaN/GaN/SiC and AlGaN/GaN/sapphire heterostructures [4–8]. Classic spectrum of "yellow" photoluminescence has been observed, and great variation of a signal over the area of samples related to yellow photoluminescence has been obtained. Photoluminescence level of samples on substrates of...
silicone carbide were more heterogeneous than those of heterostructure samples on sapphire substrates. The cause of the photoluminescence heterogeneity in samples has not been still identified. However, the photoluminescence heterogeneity is an evidence of heterogeneous properties of heterostructures over their area. The peaks of photoluminescence related to band-to-band junctions have not been detected for GaN and AlGaN layers, which may be explained by insufficient intensity of sample exposure to LED radiation.

Based on the data obtained for inward non-destructive testing of wafers, the device for automatic drawing of "photoluminescence maps" over the sample area [6] has been developed and commissioned. It allows monitoring of 48 sections of photoluminescence for heterostructures with a diameter of 2 inches or 108 sections of photoluminescence for heterostructures with a diameter of 3 inches.

4. Conclusion
When recording cathodoluminescence in AlGaN/GaN heteroepitaxial structures at room temperature, selection of energy of exciting electrons allows clearly identifying spectrum components of exciton radiation even from thin layers of AlGaN and AlN, which allows determining the composition of triple compound of AlGaN.

High heterogeneity of AlGa/N/GaN structures has been proven by the fact that the intensity and ratio of exciton radiation components remained almost unchanged over the wafer area.

Effective method of assessment of AlGaN and AlN layer location depth in structures is a variation of energy of a primary electron beam.

Wide bands of 480 to 700 nm corresponding to "yellow" luminescence with a maximum value near 540 nm have been observed in all AlGaN/GaN structures, which was caused by defects in GaN layers.

Radiation band from an optical center with a zero phonon line of 237 nm (quantum energy is 5.2 eV) and the phonon repetition range of 243 to 266 nm has been observed in luminescence spectra. Existence of this band is apparently related to defects of the AlN layer.

"Yellow" luminescence related to defects of wafers with AlGaN/GaN heterostructures was clearly visible in photoluminescence spectra excited by UV LED, which justified the use of a photoluminescence method for quality control of original wafers by recording of "photoluminescence maps."

Acknowledgments
Research was supported by the Ministry of Education and Science of the Russian Federation (No 8.5098).

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