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Magnetron sputtering deposition of ITO films on semiconductor heteroepitaxial structures surface

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Abstract. The paper presents the results of developing a technology for depositing a current spreading layer based on ITO (indium tin oxide) films onto the surface of a p-GaN LED heteroepitaxial structure InGaN/AlGaN/GaN. In order to eliminate the bombardment of the semiconductor heteroepitaxial structure by high-energy charged particles, the paper studies the efficiency of various methods for removing gas discharge plasma from the substrate and localizing it near the surface of the sputtered target. For the same purpose, the efficiency of using buffer coatings deposited onto the surface of the heterostructure before applying the ITO film is studied. It is shown that the most effective solution for protecting the surface of the heterostructure is the deposition of a two-layer structure: a thin In+Sn metal film deposited by magnetron sputtering of an In(90%)/Sn(10%) target in an oxygen-free environment and the main ITO film deposited in the same vacuum cycle with the addition of oxygen. This combination allows to provide values of specific contact resistance of ITO/p-GaN at the level of $8 \cdot 10^{-4}$ Ohm·cm^2 with a transmittance of 94% at a radiation wavelength of 450 nm.
Keywords: ITO, current spreading layer, ohmic contact to p-GaN.

1. Introduction

At present, the most common methods of depositing thin-film coatings in the manufacture of micro- and nanoelectronic devices are electron-beam evaporation and magnetron sputtering. At the same time, some issues related to the application of various functional coatings (current spreading layers, antireflection coatings) specifically to heteroepitaxial structures in the manufacture of optoelectronic devices remain unresolved. This is due to the fact that the most acceptable method of vacuum deposition of coatings on the surface of such structures is electron-beam evaporation. When applying coatings by magnetron sputtering, the heterostructure of the device is subjected to significant bombardment by high-energy charged particles. This causes the appearance of radiation defects in it and leads to the degradation of its characteristics [1].

On the other hand, the deposition of materials by magnetron sputtering with changes in various process parameters allows a very wide range of modification of the resulting coatings. Thus, this method has significant advantages in cases where one of the following requirements for the film material and its properties is important: multicomponent materials, heat-resistant materials, dielectric films, good adhesion, low-temperature deposition, thickness uniformity over a large area [2].

Thus, the urgent problem is to improve the technology of deposition of functional thin-film coatings by magnetron sputtering on the surface of heteroepitaxial structures without the formation of radiation defects in them. The purpose of this work is to develop a technology for deposition of a current spreading layer based on ITO (indium tin oxide) films on the surface of a p-GaN LED heteroepitaxial structure InGaN/AlGaN/GaN without its degradation and with minimal ITO / p-GaN contact resistance.

1. ITO Film Deposition Technology

The ITO films were deposited by reactive magnetron sputtering of an In-Sn target (90% indium, 10% tin) in a working atmosphere of argon (90%)/oxygen (10%) gas mixture on an EPOS-PVD thin film vacuum deposition unit. The substrate temperature during deposition was maintained at 300 °C. The discharge current was 0.3 A, and the deposition time was 50 minutes. Immediately after deposition, the ITO films were subjected to additional thermal annealing in the working chamber for 40 minutes at a temperature of 400 ºC. Carrying out high-temperature annealing of the ITO films immediately after their deposition contributes to a significant decrease in their specific resistance due to the appearance of a crystalline structure and an increase in the concentration of conduction electrons caused by the formation of oxygen vacancies, which are donor centers. The thickness of the ITO films deposited under such conditions was 120 nm. The technology used for ITO deposition and the study of its electrophysical properties are described in detail in [3, 4].

2. Deposition of ITO films on the surface of heteroepitaxial structures

To achieve the objective set in the paper, two tasks were performed. First, the efficiency of eliminating the influence of bombardment of a semiconductor heteroepitaxial substrate by high-energy charged particles was investigated using a magnetic deflection system and buffer coatings deposited on the substrate surface before applying an ITO film. The second task is related to ensuring the minimum contact resistance of the ITO / p-GaN contact. The solutions of the tasks is described in this section.

2.1. Using a magnetic deflection system

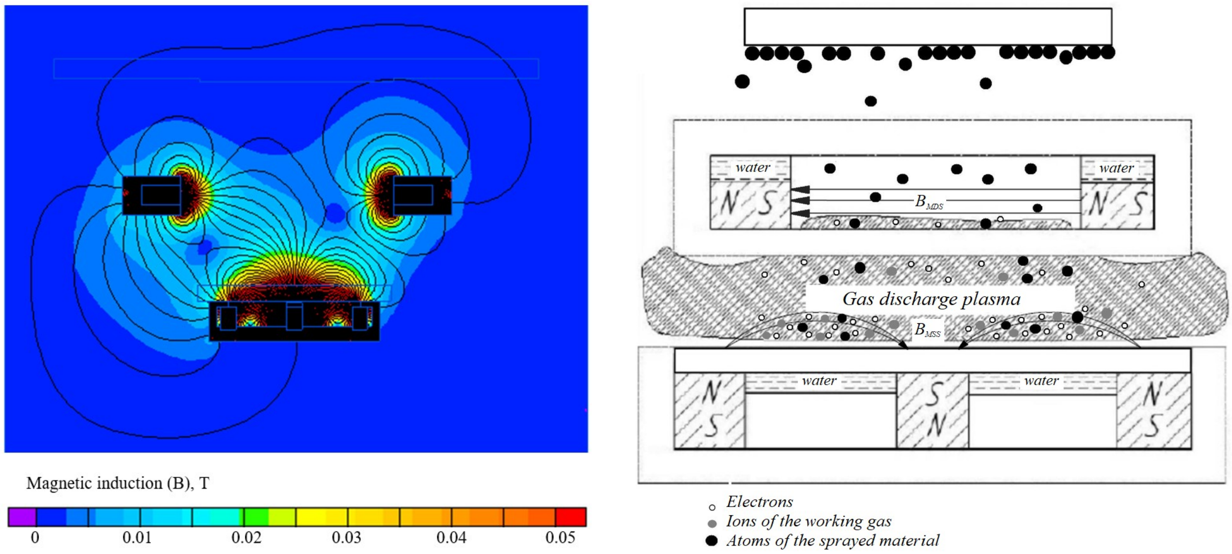
Analyzing the results of the work of various teams, cited in [5–9], the most technologically advanced method seems to be the elimination of electron-ion bombardment using the "magnetic bias" effect, which can be implemented in a standard magnetron sputtering system (MSS) of a planar type with one cathode, if it is equipped with reflective elements. Thus, by creating a magnetic field between the MSS cathode and the substrate, parallel to the surface of the cathode, it will act on high-energy charged particles during the sputtering process, deflecting them from the surface of the substrate by the Lorentz force, preventing its bombardment.

In order to ensure the closest possible picture of the propagation of the magnetic field strength vector of the magnetic deflection system (MDS) to the intended one, a simulation of possible MDS variants was carried out.

The analysis of the obtained magnetic field line models with the use of the described MDS taken into account showed that the most effective system is a planar MDS with two co-directional magnets (Figure 1a). This is due to the fact that of all the considered MDS, only planar MDS provide a magnetic field orthogonally directed to the charged particles moving toward the substrate. In order to determine the most optimal ratio of the magnetic induction values of the permanent magnets used in the MSS and MDS, further modeling of the MOS with two co-directional magnets was carried out at different values of their magnetic induction. The modeling was performed at a constant magnetic induction value of the MSS magnets. The magnetic induction value of the MDS magnets varied relative to the MSS magnets in the following ratios (MSS/ MDS, respectively): 1/2; 1/1; 2/1; 4/1. The modeling results showed that the most optimal ratio of the magnetic induction values of the permanent magnets used in the MSS and MDS is 2 to 1.

Taking into account the design parameters of the MDS determined by modeling, a magnetic system was created that deflects high-energy charged particles of gas discharge plasma passing through it, made in the form of a rectangular steel housing with magnets fixed in it on two opposite sides in such a way that the magnetic field created by them in the internal part of the system was directed orthogonally to the movement of atoms of the sputtered target deposited on the surface of the semiconductor heteroepitaxial structure.

A schematically created deflection system, made in the form of a rectangular steel housing with permanent magnets fixed in it on two opposite sides, is shown in Figure 1b. The deflection system is placed between the planar type MSS, which includes a magnetic system and a sputtered cathode and a substrate, on the surface of which the sputtering is performed. Cooling of the magnets is carried out with running water.



(a) (b)

Fig. 1. Results of modeling the magnetic deflection system (a) and its design (b).

The efficiency of the charged particle removal system was assessed during the deposition of low-resistance optically transparent conductive ITO films on glass-ceramic substrates using a planar-type magnetron sputtering system with a magnetic field on the surface of the sputtered cathode of B_{MSS} = 0.25 T and an ion current density on the target of 14 mA/cm^2. To assess several methods, the effect of gas discharge plasma was reduced by applying a negative potential of –100 V to the substrate relative to the anode during deposition, by using the developed MDS, and by combining these methods.

The measurement of the gas discharge plasma parameters was performed by a single Langmuir probe installed near the substrate. It allowed us to measure the probe current-voltage characteristic of the plasma discharge, from which the temperature of the electrons reaching the substrate and their concentration were calculated. The calculated main parameters of the gas discharge plasma in the substrate area are given in Table 1.

Table 1. Main parameters of gas discharge plasma in the substrate area.

Plasma Influence Method	Electron temperature, K	Plasma concentration, m^{-3}	Film parameters
Absent	59763	$5.95\cdot10^{12}$	ρ_S = 12.8 Ohm /□ d = 130 nm
Applying a deflection potential to the substrate –100 V	50877	$5.94\cdot10^{12}$	ρ_S = 19 Ohm /□ d = 130 nm
Application of magnetic deflection system	16738	$4.5\cdot10^{11}$	ρ_S = 74 Ohm □ d = 95 nm
Combination of both methods	11164	$4.47\cdot10^{11}$	ρ_S = 60 Ohm /□ d = 170 nm

The conducted studies showed that the supply of a negative potential to the substrate gave only a small decrease in the electron energy, without affecting the concentration of charged particles in the plasma. The most effective method for reducing the effect of gas discharge plasma on the substrate and the growing film was the elimination of electron-ion bombardment by a magnetic removal system. This resulted in a decrease in the energy of electrons reaching the substrate by more than 3.5 times, but their concentration in the area decreased by only an order of magnitude.

During the experiments it was established that the decrease in the influence of the gas discharge plasma on the growing film caused a decrease in the growth rate and an increase in resistance. Upon a more detailed study of the film surfaces it was noted that the obtained films with low surface resistance, deposited without removing the plasma from the substrate, had a smooth homogeneous structure, while on the films deposited using a removal system, pronounced cracks were found, which, being defects of the films, undoubtedly increased their surface resistance.

Film cracking during its deposition using MDS is caused by the fact that, by removing high-energy electrons from the substrate, which heated it, the substrate temperature was significantly reduced during deposition. Measurements of the substrate temperature during the deviation of the gas discharge plasma from the substrate showed its decrease by 100–120 °C. As a result, strong mechanical stresses arise in the growing film. In addition, the interaction of the magnetic fields of the magnetron sputtering system and MDS leads to a non-uniform distribution of the gas discharge plasma over the sputtered cathode, due to which the cathode sputtering rate is non-uniform. The listed consequences complicate the use of the studied method for reducing the electron-ion bombardment of the substrate during the deposition of a low-resistance layer of ITO current spreading on the p-GaN surface.

2.2. Using Buffer Layers

To eliminate bombardment of the semiconductor heteroepitaxial structure with high-energy charged particles, we also investigated the efficiency of using buffer coatings deposited on a heterostructure surface before applying an ITO film. The best technology for depositing ITO films on a p-GaN surface using buffer coatings was selected with obtaining the minimum contact resistance of ITO / p-GaN in mind, ensuring the ohmic current-voltage characteristic of this contact, and also based on ensuring the maximum transmittance at a LED emission wavelength of 450 nm. We used the following systems Ni / ITO (10/120 nm), Ni / Au / ITO (5/10/120 nm), In + Sn / ITO (2/120 nm) as the studied contact systems based on ITO films with buffer sublayers. The contact system was obtained by magnetron sputtering of an In/Sn metal target for a short time in an Ar atmosphere to obtain a 2 nm metal layer, after which oxygen was added to the working atmosphere to form an ITO film on the substrate.

For comparison of contact resistance, a traditionally used reference ohmic contact to p-GaN based on the Ni/Au thick-film system (5/200 nm) was also prepared. The given contact systems were deposited on the p-GaN surface of the InGaN/AlGaN/GaN LED heteroepitaxial structure. The specific contact resistance is determined using the transfer length method (TLM). This method is based on measuring the total resistance between two contacts as a function of the distance between these contacts and is described in [10].

Figure 2 shows the transmission spectra of the contact systems under study. In terms of film transparency in the blue spectrum, the best results are shown by Ni/Au/ITO and In+Sn/ITO films. Figure 3 shows the volt-ampere characteristics of the contact systems under study, obtained by the Kelvin method.

The steepest volt-ampere characteristic is for the Ni/Au based contact, which indicates the lowest specific contact resistance. Table 2 shows the calculated values of specific contact resistance of the contact systems under study.

In the aggregate of parameters, the best characteristics are demonstrated by the In+Sn/ITO contact system with a specific contact resistance of $\rho_c = 8\cdot10^{-4}$ Ohm·cm^2 at a transmittance of 94% at a radiation wavelength of 450 nm. The obtained values of the specific contact resistance of the

In+Sn/ITO system correspond to the range of experimentally obtained by various teams values of the ITO / p-GaN contact from 10^{-1} Ohm·cm^2 to 10^{-4} Ohm·cm^2 [10, 11].

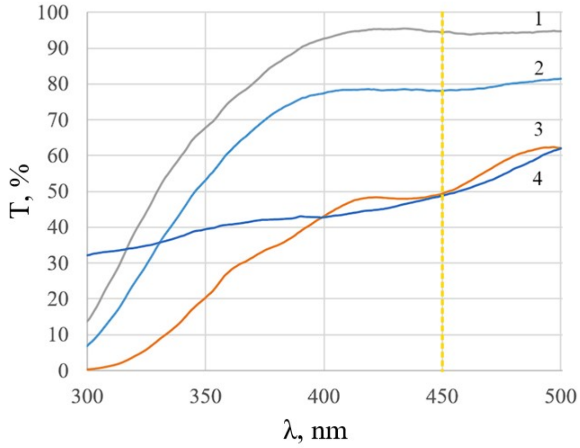


Fig. 2. Spectral dependence of the transmittance of samples: 1 – In+Sn/ITO, 2 – Ni/Au/ITO, 3 – Ni/ITO, 4 – Ni/Au.

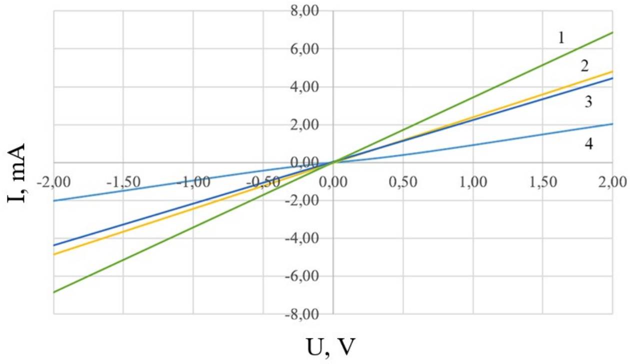


Fig. 3. Comparison of current-voltage characteristics of contacts to p-GaN: 1 – Ni/Au, 2 – In+Sn/ITO, 3 – Ni/Au/ITO, 4 – Ni/ITO.

Table 2. Specific contact resistance of the contact systems under study.

	Ni/ITO	Ni/Au/ITO	In+Sn/ITO	Ni/Au
ρ_c, Ohm·cm^2	$2.9 \cdot 10^{-3}$	$9 \cdot 10^{-4}$	$8 \cdot 10^{-4}$	$7 \cdot 10^{-5}$

3. Conclusion

As a result of the conducted research, various technologies of deposition of the current spreading layer based on ITO films on the surface of p-GaN of the InGaN/AlGaN/GaN LED heteroepitaxial structure were implemented and investigated. The first investigated method of eliminating the bombardment of the semiconductor heteroepitaxial structure by high-energy charged particles was the removal of gas discharge plasma from the substrate and its localization near the surface of the sputtered target using a magnetic deflection system. The use of this deflection system made it possible to reduce the concentration of charged particles reaching the substrate by more than 13.2 times. However, the electrical characteristics of the ITO films deposited under conditions of deflection of charged particles deteriorated significantly.

The most effective solution for protecting the heterostructure surface was the use of buffer coatings, which were a two-layer structure: a thin metal film of In + Sn deposited by magnetron sputtering of an In(90%)/Sn(10%) target in an oxygen-free environment and the main ITO film deposited in the same vacuum cycle with the addition of oxygen. This combination allows obtaining low values of the specific ITO/p-GaN contact resistance at a level of $8 \cdot 10^{-4}$ Ohm·cm^2 with high transparency.

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