The effect of AlGaAs/GaAs laser heterostructure ionic surface cleaning on the structure and properties of AlN films deposited by the method of reactive ion-plasma sputtering

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Abstract: The paper presents studies of the structural and optical properties of AlN thin films grown on an AlGaAs/GaAs semiconductor laser heterostructure with the use of preliminary ionic surface cleaning and without it. After cleavage of the heterostructure, a natural surface oxide forms on the facet. In the paper, the ionic etching regime providing the removal of the surface oxide layer without significant defects in the semiconductor heterostructure is determined.

Introduction

The most important characteristic of modern semiconductor lasers, along with power, is their reliability and durability. Usually, degradation of laser heterostructures occurs due to catastrophic optical mirrors damage (COMD) \[1\][2]. The main cause of COMD are surface defects in the active region of the facet cavity, the presence of which results in the absorption of the laser's own radiation and the appearance of nonradiative recombination. These processes leads to local heating with the breaking of chemical bonds and the generation of new defects, which, in turn, leads to the destruction of the structure. On a certain output power threshold, the laser mirror gets irreversible damage and the laser fails.

To weaken the effect of COMD, passivation of the surface of the facets is used. For example, a coating is applied to the surface of the resonator, which weakens nonradiative recombination and increases the threshold power before COMD \[2-5][7]. Passivation may be carried out chemically \[2-4][6]. The advantage of this method is that the facets are not exposed to high-energy particles. One more way is to cleave the laser structure in a vacuum and apply coating without extraction it to air, which is a technically complex and expensive \[4][5]. Another option is to carry out cleaning of the heterostructure facets surface by ionic etching in an inert gas atmosphere before applying the passivation coating. A similar work has already been presented \[7], however, in the case of ZnSe, as the authors notice, it is necessary to additionally deposit antireflective or reflective coatings over the passivation layer, which makes the process more complex. The negative side of this method is that in the process of etching it is possible to damage the structure itself. Therefore, the development of methods for forming passivation coatings of AlGaAs/GaAs heterostructures with the possibility of removing a defective layer is an actual and important problem in the technology of high-power semiconductor lasers.

In the paper we investigate the possibility of using thin AlN films as passivation coatings for high-power AlGaAs/GaAs lasers using preliminary cleaning of the facets of the heterostructures prior to passivation layer deposition to remove a layer of surface oxide that is formed naturally after cleavage of the structure in air and in further negatively affects the laser lifetime.
To carry out the cleaning, the method of ionic etching of the facets of the heterostructures was chosen. The cleaning procedure is followed by the deposition of AlN passivation coating at a single process, without extraction of the structure to air. This method allows us to clean the surface from impurities and, in contrast to chemical passivation, from the layer of native oxide, Al₂O₃, which allows it to be used for processing the aluminum-containing heterostructures [4][6].

Aluminum nitride has been chosen as a passivation coating because it has a number of features: high strength characteristics, chemical resistance, high thermal conductivity and decomposition temperature, wide variation of the refractive index. In contrast to ZnSe in [7], AlN due to its optical properties, physical and chemical resistance, can simultaneously serve as a passivating and antireflective coating for mirrors of high-power semiconductor lasers, which greatly simplifies the process and reduces its cost.

Experimental

To evaluate the effect of ionic cleaning the samples of AlGaAs/GaAs laser heterostructures obtained using MOCVD technology [8] were taken. The AlN coatings was deposited on the facets of the heterostructures after cleavage and exposition in the air for a predetermined time. In addition, control samples of AlN films deposited on an oriented GaAs (001) substrate were investigated. Deposition of AlN films was carried out by the method of reactive ion-plasma sputtering in the "UB-744" triode-type vacuum system by sputtering a target made of pure Al (99.999%) in N₂ atmosphere. As a working gas for ionic cleaning, Ar was used. The purity of working gases is not worse than 99.99%. The residual pressure before the process was not higher than 1.0x10⁻⁶ Torr. The pressure of working gases during ionic cleaning and during the deposition process was maintained at 2.0-3.0x10⁻³ Torr.

The thickness and refractive index of all films were evaluated on the LEF-3M-1 ellipsometer at a wavelength of 633 nm. The structure of the films was studied with scanning electron microscopy using the Supra 25 microscope. Quantitative analysis of SEM images was carried out using the DIAna TEM program [9].

To estimate the results of ionic etching, a special series of thin film samples was prepared with a variation in the time of formation of the oxide layer from 30 to 120 minutes, with and without the ionic cleaning procedure. The accelerating voltage on the sample holder during the ionic cleaning process was +30 V.

Results and discussion

The thickness of the films measured by ellipsometry was from 220 to 240 Å for samples prepared for estimation of the results of ionic etching. The refractive index for these samples ranged from 1.994 to 1.997. Typical thickness values for control samples of films grown in working processes are 650-800 Å, and the refractive index is 2.00-2.08 (Fig. 1). For films thicker than 700 Å, an additional thickness estimation with the SEM images was carried out. The results of thickness measurements with SEM and ellipsometry are in good agreement. Taking into account the measured
control samples, a tendency to increase the refractive index while increasing film thickness was found. The increase in the refractive index while increasing film thickness can be explained by the fact that at the beginning of the process aluminum nitride grows in the amorphous phase because of large mismatch of the lattice parameters with GaAs, gradually converting to microcrystalline phase, as the thickness of the films grows. This effect is especially noticeable in the presence of residual oxygen in the chamber, as was previously observed in [10].

![SEM image of an AlN film deposited on an AlGaAs structure, 120 min exposure to air with etching](image1)

Fig. 2. SEM image of an AlN film deposited on an AlGaAs structure, 120 min exposure to air with etching

![Distribution of the relative intensity of secondary electron emission for different samples](image2)

Fig. 3. Distribution of the relative intensity of secondary electron emission for different samples

The SEM image of the surface of the AlGaAs laser structure after ionic cleaning and deposition of the AlN film is shown in Fig 2. Figure 3 shows the results of a quantitative analysis of the intensity of secondary electron emission from samples prepared under different conditions. The changes in the intensity of the SEE reflects the features of the chemical composition of the various regions of the heterostructure. One can see transitions between layers and the presence of a quantum well, expressed by a local increase in intensity at around 2500 nm. It has been found that for samples that were not undergo ionic cleaning, the contrast of the images increases, and the resolution decreases with increasing of oxidation time from 30 to 120 min before deposition of AlN. For samples obtained with the use of ionic cleaning, a weak dependence of the image quality on the oxidation time is observed. This allows us to conclude that the surface condition of the samples is comparable after cleaning, regardless of the time of formation of the oxide layer. The results obtained can be explained by the processes of destruction of the oxide layer and sputtering of oxygen when bombarded with argon ions. At the same time the refractive index of films deposited after the ionic cleaning procedure is usually higher than for films deposited on an oxidized surface (2.0-2.08 versus 1.98-1.99).
A study to estimate the degradation time of laser structures revealed a significant increase in the lifetime of the structure when an AlN coating was used for passivation of the facets instead of the SiO\textsubscript{2} that was used previously (Fig. 4). With a pump current of 2.6 A, the laser with a SiO\textsubscript{2} mirror starts to degrade in less than an hour and quickly fails. At the same time, laser with an AlN mirror was able to work for more than 150 hours with a gradual increase in pump current, including more than 100 hours at currents exceeding 2.5 A. The onset of gradual degradation for laser passivated with AlN is noticeable at pump currents above 3.5 A. While working with a pumping current of 3.9 A, a power drop from 2.73 to 2.6 W was observed in 25 hours for AlN-passivated laser.

**Conclusion**

The results of the studies show the advisability of using aluminum nitride films as a passivation coating for the high-power semiconductor lasers facets. Incorporation of the stage of preliminary ionic surface cleaning into the deposition technology also seems reasonable due to the improvement in the quality of deposited coatings and the increase in the reliability and longevity of lasers. At the same time, more detailed studies of the possible damage to the structure in the process of ionic etching are needed, and further improvement of the deposition technology is required to effectively control the quality of the coatings.

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