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# Influence of ion cleaning of front facet of 9xx nm InGaAs/AlGaAs/GaAs diode lasers on their maximal output power

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This paper reports on the study of the effect of ion cleaning of emitting cleaved facet of 9xx nm laser diodes based on InGaAs/AlGaAs/GaAs on their limiting radiation power. Measured maximal power and the percentage of laser diodes with a visual manifestation of catastrophic optical damage in the active region were analyzed. It was found that short-term (1 min) low-energy treatment with argon and hydrogen ions does not lead to changes in the parameters of laser diodes, while treatment with nitrogen ions results in a decrease in the maximal output power and an increase in the probability of catastrophic optical damage. It is also shown that the use of an ion source based on electron cyclotron resonance leads to better results compared to a End Hall source or radiofrequency source with inductively coupled plasma, due to the lower energy of the ions.

**Keywords:** Ion cleaning, laser diode, catastrophic optical damage, maximal output power, passivation, nitridization.

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## 1. Introduction

Currently, methods are being actively developed that increase the maximum output power of laser diodes and laser lifetime [1–3]. One of such methods is passivation of the emitting facet of semiconductor laser. The term „passivation“ means that the chemical activity of the semiconductor surface is reduced, the number of non-radiative recombination centers decreases, oxides present on the surface are removed [4]. One of the objectives of passivation is to remove gallium and arsenic oxides from the surface. The oxides themselves do not adversely affect the performance of laser diodes, however, as was shown when calculating the phase diagrams of the system Ga-As-O, (Thurmond et al. [5]), $As_2O_3$ cannot exist in thermodynamic equilibrium with GaAs. Arsenic oxide produced on the surface of gallium arsenide cleavage in the atmosphere slowly interacts with GaAs even at room temperature [6]:

$$As_2O_3 + 2GaAs \rightarrow Ga_2O_3 + 4As \ (\Delta G = -62\,\text{kcal/mol}). \quad (1)$$

This results in the formation of a subsurface segregated layer of arsenic atoms which constitute non-radiative recombination centers. Accordingly, the purpose of passivation of the semiconductor laser facet is to ensure the absence of oxygen on the surface of gallium arsenide. This task can be solved in several ways. The first approach to solving this task is to create such cleaving conditions in which the formed facet does not have any access to oxygen. This can be achieved by cleaving in an ultra-high vacuum [7–9].

The second approach is that no measures are taken to prevent oxidation during cleavage, but before the deposition of the protective coating, ion cleaning of the surface is conducted with low-energy hydrogen ions [10–13], nitrogen [13,14] or argon [15,16] to remove oxides formed during exposure in the atmosphere. The second approach is easier to implement, since it does not require manipulations with a fragile semiconductor wafer in a vacuum or in an inert medium, however, due to the possibility of radiation defects, a number of authors note that treatment with low-energy ions can reduce the maximum output power and service laser diode lifetime [4,17]. In this regard, the effect of ion cleaning of the surface of the emitting chip of 9xx nm laser diodes based on InGaAs/AlGaAs/GaAs on their maximum radiation power was investigated in this paper.

## 2. Experiment procedure

A semiconductor structure with a wavelength of 965 nm containing Al in waveguide and emitter layers (the mole fraction of aluminum $(x)$ is up to 0.3 and up to 0.5, respectively), and InGaAs [18] quantum well was used to study the impact of ion cleaning of the emitting facet of laser diodes on their maximum output power.

The ion cleaning of the surface was performed on three different types of ion sources to exclude the impact of the type of ion source on the results of the experiment. The first type is a End Hall ion source manufactured by LLC „Izovac“, the second is an ion source based on electron

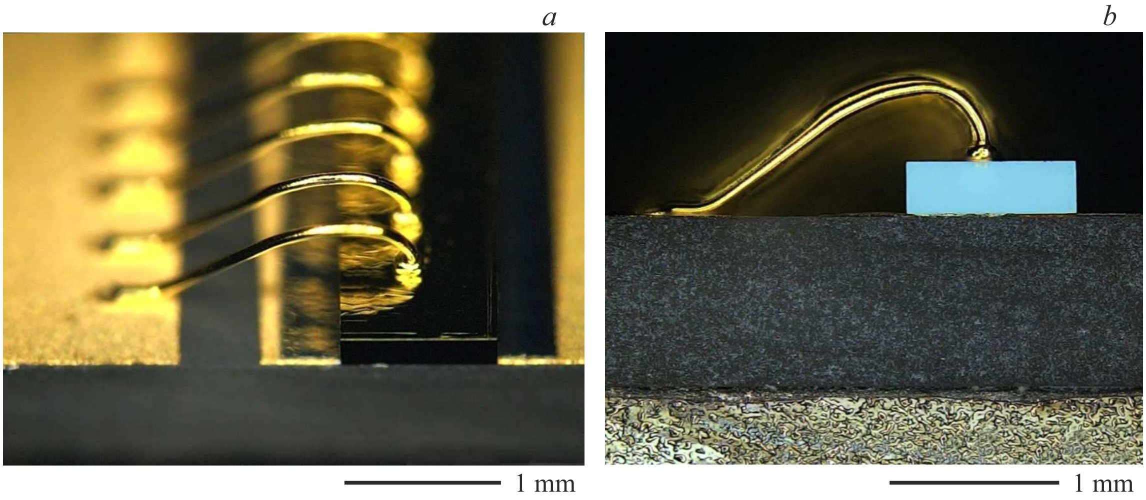


**Figure 1.** The mounted laser diode on the submount: *a* — top view, *b* — front view.

cyclotron resonance (PCS-ECR) manufactured by SPECS GmbH, the third one is an ion radio frequency source with inductively coupled plasma (RF-ICP) Copra manufactured by CCR GmbH. Nitrogen, hydrogen and argon were used for cleaning.

To minimize the introduction of radiation defects, the processing time in all cases was minimal and amounted to 1 min. The operating mode of all sources was also chosen so that to minimize the ion energy. The ECR source operated in the Atom Beam Mode when the plasma was generated only by powering the magnetron with a current of 50 mA without further acceleration of the ions formed in the plasma, with energies of $\leq 10$ eV. Thus, the stream at the outlet of the source consisted mainly of atoms and molecules. RF-ICP source operated at a power of 1000 W that ensures the highest ion current density and ion energy from 15 eV. The End Hall ion source operated at the lowest possible voltage, providing plasma generation and amounting to 50 V, at which ionization of the gas supplied to the source occurred. The ion energy in this case was 30 eV. It should be noted that it was not possible to produce an ion current at a End Hall ion source when hydrogen was supplied to it, however, the results of this experiment are still provided in this paper, since part of the supplied gas could be ionized on a red-hot tungsten spiral, and part in the gap between the anode and cathode.

After the ion cleaning process, stacking frames with laser chip lines were removed from a vacuum chamber with an ion source and placed into a vacuum unit „Ortus" (LLC „Izovac") with an electron beam evaporator and a End Hall ion source of assistance for applying a protective coating to the emitting facet. The pressure in the chamber before the start of the passivation process was $10^{-4}$ Pa, temperature 150°C. A quarter-wave ($\lambda/4$) coating of $Al_2O_3$ was applied to the output facet of the laser diodes by electron beam evaporation with ion assisted oxygen. A quarter-wave interference coating $TiO_2/SiO_2$ of 16 layers was applied to the back facet, providing a reflection coefficient of > 99%.

A similar process of deposition the front and rear mirrors was performed on a stacking frame with reference lines of laser chips, which were not subjected to preliminary ion cleaning and were loaded into a vacuum unit immediately after scribing the semiconductor wafer.

The maximum output power of the mounted laser diodes was measured in a pulse mode, at a pulse repetition frequency of 50 Hz and a duration of 1.15 microseconds. The set current was monitored using Tektronix TDS 2012C oscilloscope, the emitter power was measured by a photometric sphere SF-007/2 with a meter IM-03T.

## 3. Experimental results and discussion

The list of experiments is provided in the table.

According to the results of each experiment, 10 laser diodes with a cavity length of 4 mm and a emitter width of 90 microns were mounted on AlN substrates. Ultrasonic micro-welding of contacts to the *n*- side of the crystal was

List of experiments to study the effect of ion cleaning on the maximum output power of laser diodes

| № experiment | Source Type | Gas |
|---|---|---|
| 1 | – | – |
| 2 | RF-ICP | $N_2$ |
| 3 | RF-ICP | Ar |
| 4 | RF-ICP | $H_2$ |
| 5 | PCS-ECR | $N_2$ |
| 6 | PCS-ECR | Ar |
| 7 | PCS-ECR | $H_2$ |
| 8 | End Hall | $N_2$ |
| 9 | End Hall | Ar |
| 10 | End Hall | $H_2$ |

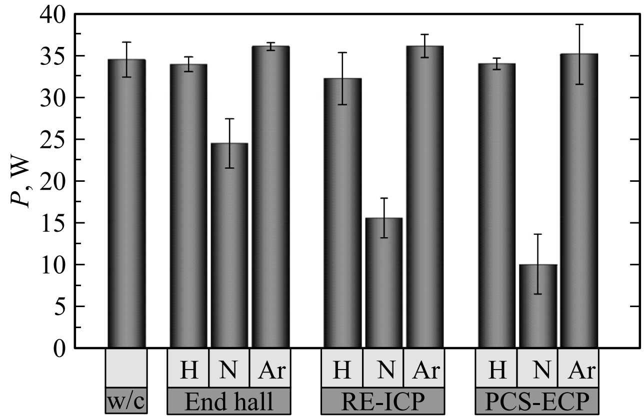


**Figure 2.** Diagram of the dependence of the average maximum output power of laser diodes depending on the type of ion cleaning.

performed by gold wire using the „ball-wedge" method. The appearance of the mounted laser diode is shown in Fig. 1.

The power current characteristic of each chip was measured. The pumping current increased until a sudden drop in output power was observed. The average value of the maximum output power with a confidence interval of $3\sigma$ is shown in Fig. 2.

According to Fig. 2, the impact of nitrogen ions on the surface of the emitting facet results in the decrease of the maximum output power of laser diodes. While the impact of hydrogen and argon ions does not cause any change of the maximum output power. The obtained result is consistent with the paper [19,20], in which it was shown that nitridization of the facet of a laser diode can lead to negative results due to a reaction:

$$GaAs + N \rightarrow GaN + As, \qquad (2)$$

as a result of which, just as in the case of a reaction with oxygen, arsenic atoms are produced which constitute non-radiating recombination centers. At the same time, as shown on Fig. 2, short-term (1 min) exposure to low-energy ions does not cause any radiation defects in an amount sufficient to reduce the maximum output power, which is consistent with the data of the authors of the paper [17], in which the negative impact of ionic cleaning by argon began to manifest itself after 2 hours of ion cleaning.

Additionally, each laser diode was examined for any signs of catastrophic optical degradation (COD) in the active region from the side of the emitting facet using brightfield microscopy. An example of optical degradation after the laser diode reaches the maximum output power is shown in Fig. 3.

It should be noted that visually degradation was observed only on a part of the laser diodes, while the other part had no signs of destruction, despite an irreversible decrease of output power. Based on the data obtained, a statistical diagram was plotted, shown in Fig. 4, demonstrating the percentage of laser diodes with visible destruction of the active region and waveguide after reaching the maximum output power.

As shown on Fig. 4, the largest percentage of visually observed optical degradation is associated with the diodes treated with nitrogen ions, which is consistent with the average maximum output power measurement data (Fig. 2). In addition, it can be noted that laser diodes that were processed using an ECR source have the lowest percentage of visually observable COD, which may be due to the fact that this type of source provides the lowest ion energy in the plasma. At the same time, the percentage of observed degradation in laser diodes treated with hydrogen using a End Hall ion source differs slightly (by 10%) from the percentage of observed degradation of untreated diodes. Also, the maximum power of these laser diodes and untreated laser diodes coincides within the confidence

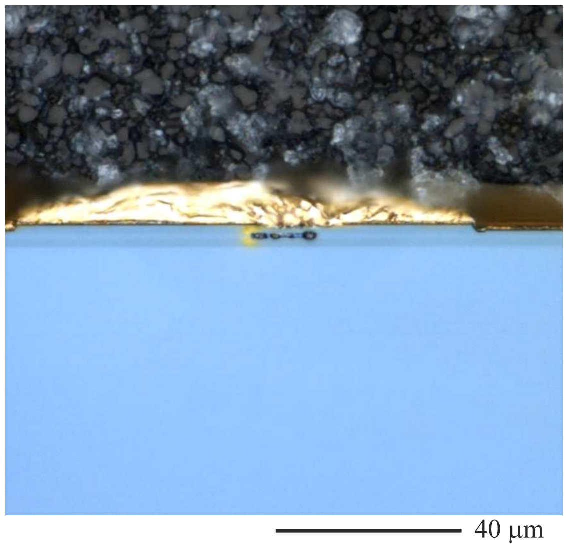


**Figure 3.** Catastrophic optical damage in the active region of the laser diode.

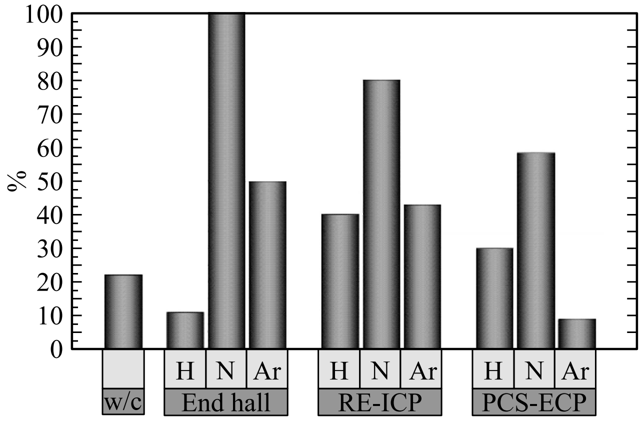


**Figure 4.** Diagram of the dependence of the percentage of laser diodes with visual signs of optical degradation from the ion cleaning mode.

interval. Both of these circumstances indicate that in the absence of an ion current, hydrogen ionization in the anode gap and on a red-hot tungsten spiral can be neglected. In laser diodes treated with argon and hydrogen using an ECR source, the percentage of observed degradation also differs slightly ($\leq 10\%$) from the percentage of observed degradation of untreated diodes. At the same time, an increase of the percentage of diodes with catastrophic degradation is observed in the case of treatment with these gases using the RF-ICP source. This may be due to the fact that during the operation of the RF-ICP grid source, its tungsten grid is slightly diffused, which leads to contamination of the treated surface.

## 4. Conclusion

In the result of performed tests it was demonstrated that short-term (1 min) low-energy treatment with argon and hydrogen ions using End Hall, PCS-ECR and RF-ICP ion sources of the emitting chip 9xx nm laser diodes based on InGaAs/AlGaAs/GaAs does not result in any reduction of the maximum output power. At the same time, the probability of visually observed catastrophic optical degradation does not increase in the case of argon ion treatment using a PCS-ECR source. Low-energy treatment with nitrogen ions, regardless of the type of ion source used, leads to a decrease in the maximum output power and an increase in the probability of visually observed catastrophic optical degradation. In addition, the use of a PCS-ECR type source leads to better results compared to an End Hall and RF-ICP source due to lower ion energy.

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### Conflict of interest

The authors declare that they have no conflict of interest.

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