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Effect of the energy of ion-chemical etching of GaAs/Al_xGa_{1-x}As structures on photoluminescence and degradation of devices

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***Abstract*. The process of ion-chemical etching of mesa-stripes in epitaxial GaAs/Al_xGa_{1-x}As structures on a setup with an inductively coupled plasma source is studied. The advantage of the setup is a high plasma density in the etching area and, therefore, a low ion energy (100 – 200 eV), which can be varied independently of the RF power. The process is developed for forming narrow (3 – 5 μm) mesa-stripes with a side-wall tilt of $\sim 85°$ and the scatter in the values of geometrical parameters equal to ± 1 % in the etching area of diameter 150 mm. It is shown that, unlike RF etching, the decrease in the photoluminescence intensity in GaAs/Al_xGa_{1-x}As structures is stabilised at the 15 % – 20 % level of the initial intensity even when the etching area is located only at a distance of 100 – 150 Å from the active region. Comparative tests are performed for ridge superluminescent diodes manufactured by using RF radiation sources and inductively coupled plasma.**

Keywords: *inductively coupled plasma source, epitaxial structure, semiconductor laser, mesa-stripe, photoluminescence intensity.*

1. Introduction

Ion-chemical etching (ICE) has been widely used for the last years for manufacturing various optoelectronic devices based on group III – V semiconductors: diode lasers, vertical-cavity surface-emitting lasers, superluminescent diodes, optoelectronic schemes, and laser linear arrays. The developed methods are based either on ICE or its combination with liquid-phase chemical etching [1].

A distinctive feature of wide-gap electronic materials (GaAs, InP, and their solutions) is their high sensitivity to the ion action, which can increase the rate of surface recombination [2] and intrinsic absorption [3], and result in the appearance of electronic traps of deep levels [4]. Therefore, the lowering of ion energy upon ion-chemical etching is an important additional requirement imposed on ion sources.

This problem is more and more often solved abroad by using etching in microwave systems in the Cl_2 atmosphere [5]. However, the developed ultrahigh-vacuum setups with microwave sources are rather complicated and expensive. In our opinion, inductively coupled plasma (ICP) sources [6], in which the high-density (up to 10^{12} cm^{-3}) plasma is produced and which can be considered as an energy 'analogue' of microwave sources, are more promising for industrial applications. The design of these systems is much simpler and they are cheaper and have a higher productivity. In this connection the use of ICP sources in the technology of semiconductor light-emitting devices is of great practical interest. In this paper, we studied the fabrication of active elements of narrow mesa-stripe lasers with a ridge waveguide in a setup with an ICP source and also analysed the energy action of etching on the emission properties of manufactured structures and durability of devices.

2. Experimental

Investigations were performed on an ERA-2M setup equipped with an ICP source developed at the Tirs Research and Production Association (Zelenograd). The principal scheme of the modernised setup is shown in Fig. 1. The source representing a coil for plasma excitation closed with a quartz cap (the so-called antenna) is fixed on a cooled coaxial RF power lead on the upper cover of a technological chamber. The plasma being produced is the 'last loop' of the excitation coil. A hermetic optical channel for the beam of an interferometer based on a He – Ne laser passes through the antenna. The beam is used to control the etching depth during the process. A water-cooled working table is connected to an RF generator ($f = 13.56$ MHz) through a matching device to control independently the bias potential. The table has a gas distributor supplying concentrically uniformly a gas mixture to the working region.

This setup had no lock evacuation, which completely excluded the possibility of using pure Cl_2. At the same time, the use of $SiCl_4$ provided high reproducibility and rate of etching multilayer GaAs – Al_xGa_{1-x}As structures and eliminated the corrosion damage of the equipment.

Preliminary tests of the setup by using $SiCl_4$ showed that the setup and source design provided stable operation in the following regimes:

(i) The ICP source power is in the 300 – 600-W range (the minimum and maximum powers are limited by the possibility of sustaining the discharge in the chamber and the generator used, respectively).

(ii) Power supply to the table is from 30 to 150 W.

(iii) Pressure in the chamber during etching is in the range from $2 \times 10^{-1} - 1 \times 10^{-3}$ Torr (the maximum pressure is limited by the stability of discharge ignition, and the

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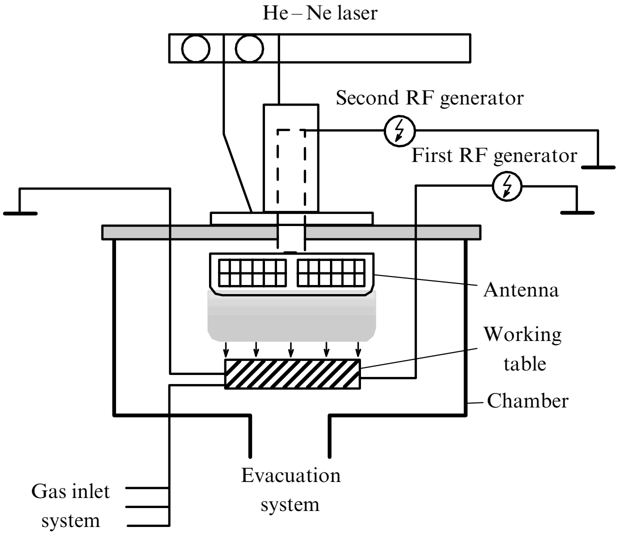

Figure 1. Principal scheme of the modified working chamber of the ERA-2M setup with the ICP source.

minimum pressure – by the gas supply regulator and evacuation system).

The most important results of technological studies are presented in Fig. 2. One can see that, as the RF power in the antenna increases, the self-bias voltage decreases, resulting in a decrease in the etching rate (Fig. 2a). At the same time, a change in the antenna power does not affect appreciably the ridge geometry. The rest of conditions being the same, the tilt of side faces of a mesa-stripe remains virtually invariable (80 – 85°) and mainly depends of the quality of a photoresistive mask (PRM).

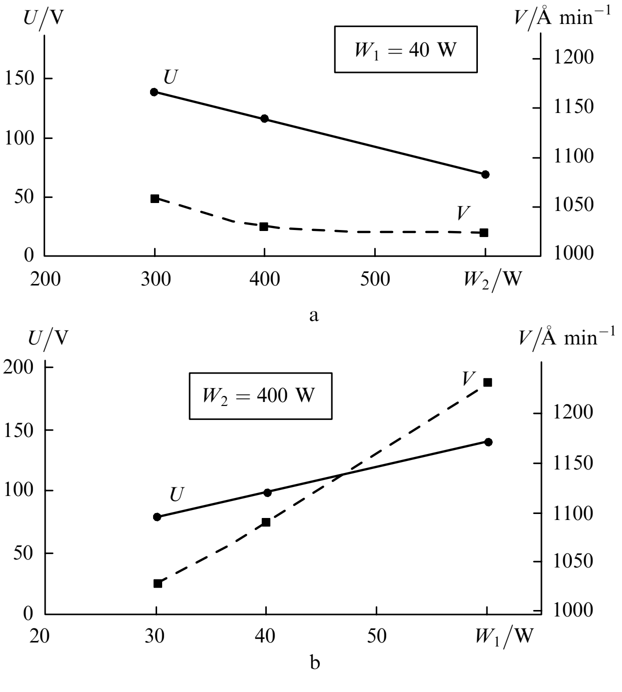

Figure 2. Dependences of the bias voltage U and the etching rate V on the RF power W_2 in the antenna for the power $W_1 = 40$ W on the working table (a) and on the power W_1 on the working table for the power $W_2 = 400$ W in the antenna (b).

As expected, the influence of power supplied directly to the target table is more substantial (Fig. 2b). As power on the table is increased, the self-bias voltage increases, resulting, under other conditions being the same, in an increase in the etching rate.

Taking into account all the requirements imposed on the etching process (the reproducibility of the ridge profile, the mirror surface, the selectivity and rate of etching, etc.), we have chosen the etching regime with the etching rate $V = 1450$ Å min^{-1} and the particle energy $E_{\mathrm{ICP}} = 150$ eV. In this regime, the deviation from the average etching depth ~ 3 μm within the working area ($d = 150$ mm) is only $\pm 1.6\,\%$. This regime was used in experiments described below.

3. Experimental results

To evaluate the outlook for applications of the source for manufacturing light-emitting devices, we performed experiments on the influence of ion etching on the electrophysical properties of an epitaxial structure. For comparison, we used the etching regime with an RF source with $E_{\mathrm{hf}} = 650$ eV.

In the first series of experiments, the effect of ion action was estimated from the photoluminescence intensity. This method has a high sensitivity and gives direct information on the effect of ICE on epitaxial layers near the mesa-stripe base.

We studied the fragments of epitaxial structures whose active areas were located between symmetric wide-gap AlGaAs layers simulating waveguide layers. The thickness of the upper waveguide in the first and second series of experiments was 1500 and 500 Å, respectively. The advantages of such samples over a substrate commonly used in experiments are obvious: the distance from a photoluminescence source (active region in the form of a single quantum well) to the surface can be determined with a high precision, while absorption of radiation in a broad waveguide is appreciable only in the presence of radiation defects.

A part of a sample under study was covered before etching with a PRM, while the other part was etched. In the first series of experiments, etching was performed in three stages, by approaching gradually the active region. At each stage, a waveguide layer of thickness 400 Å was removed. After each etching, the PRM was removed and the photoluminescence intensity was measured in adjacent regions. Then, the relative change in the photoluminescence intensity was determined, annealing was performed at 430 °C, and measurements were repeated.

The results of these studies are presented in paper [7], where the data obtained on setups using ions of different energies were analysed in detail. In this context, it is interesting to point out the following results.

We found that etching by low-energy ions (150 eV) slightly (by 15 %) reduces the photoluminescence intensity (Fig. 3). Although the final etching was performed at a distance of only 100 Å from the active region, the photoluminescence intensity ceased to decrease beginning from the residual thickness of the emitter ~ 400 Å remaining at the 85 % level of its initial value. Unlike the case of high-energy etching ($E > 500$ eV), the annealing of samples does not recover the photoluminescence intensity but further reduces it. This suggests that the decrease of the photo-

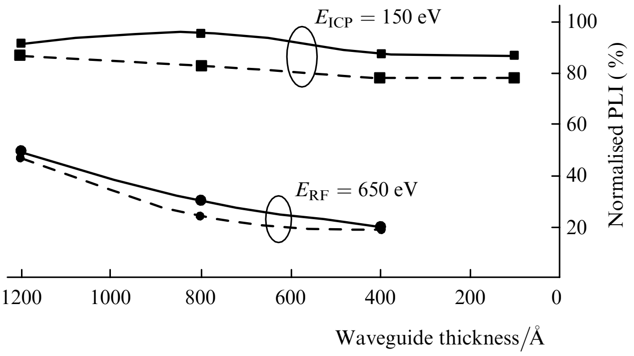

Figure 3. Dependence of the photoluminescence intensity (PLI) I/I_0 in the active region on the waveguide thickness h (I_0 is the initial photoluminescence intensity before etching for the waveguide thickness equal to 1500 Å. The dashed curves show the dependence of photoluminescence intensity after high-temperature annealing.

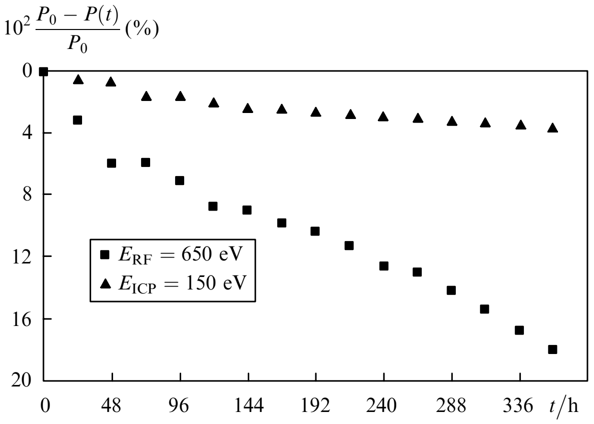

Figure 4. Results of comparative degradation tests for superluminescent diodes manufactured using RF (■) and ICP (▲) sources; P_0 is the initial radiation power.

luminescence intensity is caused most likely by the influence of surface defects. Such defects can be formed both directly during ion etching (As vacancies) and upon heating due the chemical interaction of the surface with ICE products containing Si and Cl, as well as with atmospheric gases.

This interpretation is also confirmed by the results of low-energy etching of samples in noble Ar and Xe gases. After the transfer of etched samples to the air, their photoluminescence intensity decreased by 18 %. If the surface of etched samples was coated with a ~ 0.3-μm thick ZnSe film in the same vacuum cycle, the photoluminescence intensity did not change.

In the second series of experiments, the effect of the ion energy on the photoluminescence intensity upon RF and ICP etching was studied for real light-emitting devices. This effect was estimated by a change in the radiation power during electrothermal training at a constant pump current. To exclude the influence of other factors on degradation, the devices were manufactured from halves of the same epitaxial structures, and all technological manufacturing processes (except ICE) were identical.

The etching regimes for ridge-waveguide superluminescent diodes with a skew stripe contact were the same as in previous experiments, i.e., $E_{\mathrm{RF}} = 650$ eV and $E_{\mathrm{ICP}} = 150$ eV. The operating regime of a diode for the output power $P = 1.5 - 2.5$ mW in degradation experiments excluded the contribution of degradation of near-mirror regions but provided the required current (90 mA). The temperature during electrothermal training was +55 °C. The training and measurement method was usual. The averaged results of comparative measurements of the power decrease $[1 - P(t)/P_0] \times 100\,\%$ are presented in Fig. 4 for two groups of superluminescent diodes.

For group I ($E_{\mathrm{RF}} = 650$e V), the distance h from the surface to the active region was taken to be 0.3 μm, while for devices of group II ($E_{\mathrm{ICP}} = 150$ eV), this distance was 0.23 μm. Nevertheless, one can see that low-energy etching has the obvious advantage. The total decrease in the radiation power for devices of group II during four days is 1.75 %, the decrease being 0.5 % for the first two days and only 0.15 % for the next two days, which substantially surpasses the requirements to the devices of this class.

On the contrary, devices of group I degraded under similar conditions at a greater rate – from 3.13 % during the first day to 2.1 – 2.7 % during the next 14 days. In this case, no tendency to a decrease in the degradation rate was observed.

In summary, the results of both series of experiments are as follows:

(i) A good correlation was observed between the decrease in the photoluminescence intensity and the degradation rate of superluminescent diodes with increasing ion energy upon ICE. This suggests that both these processes are determined by defects produced in the near-surface layer of a semiconductor.

(ii) The ICE process in an ICP source with $E_{\mathrm{ICP}} = 150$ eV, in which a thin near-surface layer is damaged, does not affect substantially the degradation of light-emitting devices (at least, for real distances between the etched area and the active region used in experiments), and the ICP source has obvious advantages over the RF system.

4. Conclusions

The ICP source provides the required accuracy of manufacturing elements within the working region ($d = 150$ mm), increasing simultaneously the surface etching rate (up to 1300 Å min^{-1}) and decreasing the ion energy. In addition, the high-quality morphology of the surface is obtained. Moreover, the ICP source allows one to change etching regimes, thereby varying the mesa-stripe geometry in a broad range. The ICP source also ensures a higher productivity than the RF system due to a better uniformity of the etching rate with the working area.

It is important to note that the optimal 150 – 160-eV ion etching regime completely satisfies the requirements to the formation of high-quality ridge-waveguide active elements [8] and minimises the radiation damage of the surface, thereby reducing the degradation rate of light-emitting dvices.

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