Effect of Ga\textsuperscript{+} focused ion beam etching on photoluminescence of AlGaAs/GaAs heterostructure.

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Abstract. The effect of focused ion beam (FIB) etching by 30 keV Ga\textsuperscript{+} on photoluminescence of AlGaAs/GaAs heterostructure is studied. During etching process, high-energy ions induce radiation defects that lead to a decrease of heterostructure internal quantum efficiency of luminescence. We used the SRIM software to simulate the radiation defects penetration depths in AlGaAs/GaAs heterostructure, then carried out FIB etching guided by received information. Annealing of the structure at 300 \textdegree C showed partial recovery of the internal quantum efficiency. Subsequent annealing at 620 \textdegree C showed almost full recovery of quantum efficiency depending on the etching depth. Experimental findings allowed us to affirm that FIB etching with subsequent annealing is a potential tool for making photonic nanodevices.

1. Introduction
Nowadays there is an increased interest in photonic integrated circuits (PICs). PICs contain a plurality of optically interconnected elements that mutually perform optical signal processing on a single chip. In comparison with electronic integrated circuits, optical signal use provides significant advantages - less heat generation, higher data transfer rates, greater bandwidth due to the variety of the multiplexing techniques (WDM, DWDM and etc.) and low crosstalk. The most common material for the manufacture of photonic circuits is silicon due to the high silicon technology development level in microelectronics [1]. Hybrid coupling technique allows integration of silicon photonic circuits with microlasers based on direct-band A\textsuperscript{3}B\textsuperscript{5} semiconductors [2,3]. It is possible to realize monolithic PIC design completely based on A\textsuperscript{3}B\textsuperscript{5} heterostructures, in this case the reliability of devices is increased and the cost of production is reduced. There are different microfabrication methods for prototyping parts of integrated circuits. Focused ion beam lithography technique is one of the most promising for prototyping PICs due to direct resist-free and maskless etching that on the one hand allows etching three-dimensional (3D) structures (where is hard or impossible to use mask) and on the other hand significantly decreases circuits fabrication cost. The factor that strongly limits the FIB application is the damages of crystalline structure that accompany the etching. This problem is rather good investigated for the ion implantation process where ions had high energy (100-300 keV) [4]. The influence of ions with energy typical for FIB (10-30 keV) on A\textsuperscript{3}B\textsuperscript{5} semiconductors has been investigated insufficiently.
2. SRIM calculations
When accelerated ion strikes the solid, it loses kinetic energy due to an interaction with the atoms of the sample. Transferred energy from the ion to the solid leads to a number of different processes such as sample heating, atomic sputtering, ion emission, etc. The most widespread concept of ion-nucleus interactions is a cascade collision model [5,6]. We used one of the most popular software package SRIM (Stopping and Range of Ions in Matter) to calculate the range of ions in solid. SRIM gives opportunity to calculate important parameters such as track length, distribution of vacancies in the target, recoil atoms, etc. TRIM (transport of ions in matter) is a part of SRIM software that uses the Monte Carlo method to calculate the interaction of ions with a target. In our work we used gallium ion source with energy of 30 keV and the target was Al$_{0.18}$Ga$_{0.82}$As layer. The distribution profiles of Ga$^+$ ions were calculated with the following parameters: accelerating voltage 30 keV and ion beam incidence angle 0°. Based on the simulation results, the distribution profiles of gallium ions are plotted. Figure 1 shows the distribution of implanted Ga$s$ and Al, Ga, As recoiled atoms along Y-axis and vacancies distribution profile. According to the SRIM calculation the point defect penetration depth is about 70 nm.

![Figure 1](image.png)

**Figure 1.** The distribution of implanted ions projected at Y-axis (a) and vacancies distribution profile (b).

3. Experiment
To study the effect of Ga$^+$ focused ion beam etching on the luminescence of a AlGaAs/GaAs heterostructure, the test double heterostructure consisting of a 1-μm thick GaAs layer enclosed between two 1 μm thick Al$_{1.8}$Ga$_{0.82}$As barriers was fabricated (figure 2). On the heterostructure surface 7 squares 50 x 50 μm with depths of 1, 150, 180, 330, 850, 1200 and 1500 nm were etched using Ga$^+$ ions at 30 keV. Figure 3 shows the optical micrograph of etched region and depth profiles of etched squares, obtained by profilometer (Ambios XP1). We study the influence of radiation defects on the quantum efficiency using photoluminescence measurement at room temperature. The pump source was a solid-state laser with 671 nm wavelength, which was focused into 10 μm spot with 0.85 NA microscope objective.

Squares 1-7 were measured. In all cases, a strong luminescence quenching was observed. At the 5, 6, 7 squares, at 0.34 kW/cm$^2$ pump level, photoluminescence was not observed. To improve the quantum yield we carried out low-temperature annealing of the sample in vacuum conditions at 300 °C. After this stage, photoluminescence from the first three squares (etching depths 1, 150 and 180 nm) was restored almost completely to the initial level. At the next stage, the structure was annealed in the arsenic atmosphere at 620° C over a period of 20 minutes.
**Figure 2.** Principal scheme of the sample (a) and bandgap diagram of the etched sample (b).

**Figure 3.** Depth profiles of the etched squares obtained by Ambios XP 1 profilometer (a-e) and the optical micrograph of the surface (f) (numbers 1-7 link squares with corresponding depth profiles).
Annealing at 620 °C gave practically full intensity recovery up to the level of non-etched surface in the first five squares. Figure 4 demonstrates comparison in photoluminescence (PL) spectrums between etched (5th square) and non-etched region together with the results of measurements of quantum efficiency before and after the annealing. Squares, triangles and circles denote different temperature of the annealing. The sixth and the seventh squares luminescence was not observed even after the second annealing. We suppose that increasing radiation defects penetration depth (compared with the results of SRIM calculations) is related to the high local temperature and to the diffusion and accumulation of point defects closer to the heterointerface in depth of the sample. Nevertheless, our results show the FIB etching at the depth of 850 nm (distance to the heterointerface 150 nm) could be used for photonics applications.

![Graph showing relative change in luminescence intensity](image)

**Figure 4.** The evolution of relative change in luminescence intensity for five different etching depths before and after two subsequent annealing.

4. **Conclusion**

In spite of the fact that FIB etching generate defects in a structure, subsequent annealing helps to heal radiation defects. Obtained results demonstrate the possibility of recovering luminescent properties of the structure after FIB etching. Our experimental findings confirm prospects of using FIB etching technique for the formation of PICs elements.
References

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