Conference materials
UDC 621.382.3
DOI: https://doi.org/10.18721/JPM.183.147

Optical studies of InGaAs/GaAs quantum well mesa structures passivated with sol-gel SiO_2

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Abstract. A remarkable increase in photoluminescence intensity for passivated mesa structures with InGaAs/GaAs quantum wells were demonstrated using the method of sol-gel SiO_2 passivation. The photoluminescence signal enhancement up to 50 times for 1.25 μm diameter mesas after passivation was observed. The obtained results are promising for use in microlasers with active region based on InGaAs quantum wells.

Keywords: sol-gel passivation, InGaAs quantum well, photoluminescence

Funding: Support of optical measurements from the Basic Research Program of the National Research University Higher School of Economics is gratefully acknowledged.

Citation: Melnichenko I.A., Shugabaev T., Gridchin V.O., Kryzhanovskaya N.V., Balakirev S.V., Solodovnik M.S., Zhukov A.E., Optical studies of InGaAs/GaAs quantum well mesa structures passivated with sol-gel SiO_2, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 18 (3.1) (2025) 237–241. DOI: https://doi.org/10.18721/JPM.183.147

Материалы конференции
УДК 621.382.3
DOI: https://doi.org/10.18721/JPM.183.147

Оптические исследования меза-структур на основе квантовых ям InGaAs/GaAs с золь-гель пассивацией SiO_2

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Аннотация. Продемонстрировано значительное увеличение интенсивности фотолюминесценции для пассивированных SiO_2 методом золь-гель меза-структур с квантовой ямой InGaAs/GaAs. Наблюдалось усиление сигнала фотолюминесценции до 50 раз для мез диаметром 1,25 мкм после пассивации. Полученные результаты перспективны для использования в микролазерах с активной областью на основе квантовых ям InGaAs.

Ключевые слова: золь-гель пассивация, квантовая яма InGaAs, фотолюминесценция

Финансирование: Оптические исследования осуществлены в рамках Программы фундаментальных исследований НИУ ВШЭ.

Ссылка при цитировании: Мельниченко И.А., Шугабаев Т., Гридчин В.О., Крыжановская Н.В., Балакирев С.В., Солодовник М.С., Жуков А.Е. Оптические исследования меза-структур на основе квантовых ям InGaAs/GaAs с золь-гель пассивацией SiO_2 // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.1. С. 237–241. DOI: https://doi.org/10.18721/JPM.183.147

Introduction

Semiconductor materials based on GaAs are widely used in modern optoelectronic devices, solar cells, and communication due to their high electron mobility and direct bandgap structure. However, one of the critical challenges limiting the efficiency of GaAs-based devices is the high density of surface states, which leads to an increased surface recombination velocity on the order of 10^5–10^6 cm/s [1]. To minimize negative factors affecting the surface of devices, various approaches have been developed for passivating the surface of radiating devices, including thin film deposition using atomic layer deposition (ALD), plasma treatment, and surface nitridation, which significantly improve the optical characteristics of GaAs structures [2].

A new promising technique for passivating microstructures is the sol-gel SiO_2 passivation method, which is attractive due to its low-temperature deposition process and high efficiency [3, 4]. Notably, sol-gel-derived SiO_2 coatings provide uniform coverage with controllable thickness (10–100 nm), leading to a substantial enhancement in the photoluminescence intensity and carrier lifetime of InGaN nanostructures [4]. In this study, we investigate the impact of sol-gel SiO_2 passivation on the photoluminescence emission properties of InGaAs/GaAs quantum well (QW) structures, demonstrating its potential for enhancing the performance of semiconductor lasers.

Materials and Methods

The epitaxial structures were grown on a GaAs (001) substrate using molecular beam epitaxy. Sample №1 consists of a 250 nm-thick GaAs buffer layer. Followed by a 500 nm-thick $Al_{0.33}Ga_{0.67}As$ barrier layer to confine carriers within the active region. The active region was grown in a 100 nm-thick GaAs layer and consisted of a single 10 nm-thick $In_{0.2}Ga_{0.8}As$ QW. Finally, the structure was capped with a 100 nm-thick $Al_{0.33}Ga_{0.67}As$ upper barrier and a 10 nm-thick GaAs layer to prevent oxidation.

In sample №2 a GaAs buffer layer was deposited, then a 50 nm thick $Al_{0.25}Ga_{0.75}As$ layer was formed to prevent the leakage of charge carriers into the substrate. Then, a 200 nm thick GaAs layer was grown with a 10 nm-thick $In_{0.2}Ga_{0.8}As$ QW layer placed in the middle, followed by 10 periods of superlattice (SL) consisting of GaAs/AlAs layers with thicknesses of 10 nm/10 nm. The structure was covered up with a 10 nm thick GaAs layer.

Microdisk mesas of various diameters from 1 to 20 μm were fabricated using photolithography and plasma etching for both structures. Samples №1 and №2 also differed in the density of the etched mesas: sample №1 had single mesostructure etched, while sample №2 had arrays of mesas etched in an area with a diameter of 20 μm.

The SiO_2 passivation shell was synthesized using the Stöber's method, which involves the hydrolysis and condensation of tetraethoxysilane in an ethanol-water-ammonia solution as follows. 2.1 mL of ethanol and 2.9 mL of deionized water were added to the sample, after which 0.012 g of the surfactant cetyltrimethylammonium bromide (CTAB) was introduced, which acts as growth centers for the SiO_2 gel structure and ensures the formation of SiO_2 gel on the entire microlaser surface. The resulting mixture was incubated for 5 min at room temperature. Then 25 μl of 20%

aqueous ammonia solution and 13 μl of TEOS were added. Then reaction mixture was maintained under stirring for 60 minutes. The thickness of the resulting SiO_2 layer strongly depends both on the reaction time and on the concentrations of reagents and estimated to be around 10 nm thick.

Photoluminescence (PL) spectra were measured using an Integra Spectra NT-MDT confocal microscope at room temperature. The excitation laser radiation (YAG:Nd 527 nm) was focused using a 20x objective (Mitutoyo, M Plan APO NIR) with numerical aperture NA = 0.4 into a spot up to approximately 5 μm in diameter with pump power density of 1 kW/cm^2. Detection was performed using a Sol Instruments MS5204i monochromator and a cooled CCD Si camera (Andor iVac).

Results and Discussion

The PL spectra of disk mesas in sample №1 were studied at room temperature before and after SiO_2 sol-gel passivation. Fig. 1, *a* shows PL spectra for mesa with 2 μm diameter. In the inset to Fig. 1, *a* there is a scanning electron microscope image of a single mesa with a diameter of 2 μm. The PL maximum in the range of 950–1000 nm characterizes the transition in a single $In_{0.2}Ga_{0.8}As/GaAs$ QW. The Fig. 1, *a* shows that the PL signal intensity for both GaAs and the $In_{0.2}Ga_{0.8}As/GaAs$ QW demonstrates strong enhancement after passivation. The maximum change in PL intensity for the ground-state transition of the $In_{0.2}Ga_{0.8}As/GaAs$ QW in a 2 and 3 μm mesa was approximately 8-fold (Fig. 1, *b*) after passivation. To compile comprehensive statistics, five mesas were examined for each diameter. An increase in PL intensity after passivation is observed across the entire range of studied mesas diameters. The significant spread of PL intensities for the 1 μm diameter mesa is due to etching defects in the mesa structures.

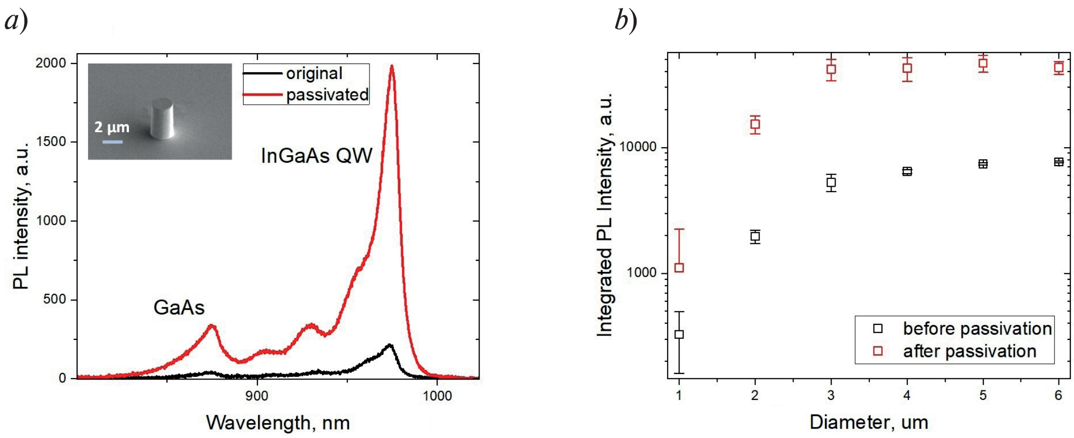

Fig. 1. PL spectra of 2 μm diameter mesa from sample №1 before and after passivation with sol-gel SiO_2 layer (*a*) integrated PL intensity for mesas of different diameter in 890–1000 nm wavelength range for structure №1 (*b*)

To verify the passivation effect and to investigate the influence of the mesa alignment further, sample №2 with a denser arrangement of mesa structures was also investigated. For sample №2, the pump laser illuminated the entire array of mesas with same diameter simultaneously. On insert to Fig. 2, *b* one can observe a scanning electron microscope image of an array of mesas with a diameter of 2 μm.

Fig. 2, *a* shows the PL spectra for an array of 1.25 μm diameter mesa structures before passivation and after passivation immediately and after 1 min of pump laser exposure. The spectra show an emission maximum associated with the GaAs/AlAs superlattice at 845 nm, GaAs at 870 nm, as well as line at 950–1000 nm characterizing the emission of $In_{0.2}Ga_{0.8}As/GaAs$ QW. Prolonged exposure to optical pumping on the surface of mesas leads to a gradual decrease in the PL signal of $In_{0.2}Ga_{0.8}As/GaAs$ QW. The observed photoluminescence decline within one minute (green spectra on Fig. 2, *a* can be related to the photopolymerization within the SiO_2 passivation layer structure under the action of optical pumping by the laser.

The PL intensity of the GaAs/AlAs superlattice also increases after SiO_2 passivation, but not as much as the QW signal (demonstrating a maximum signal amplification of 5 times for mesas with

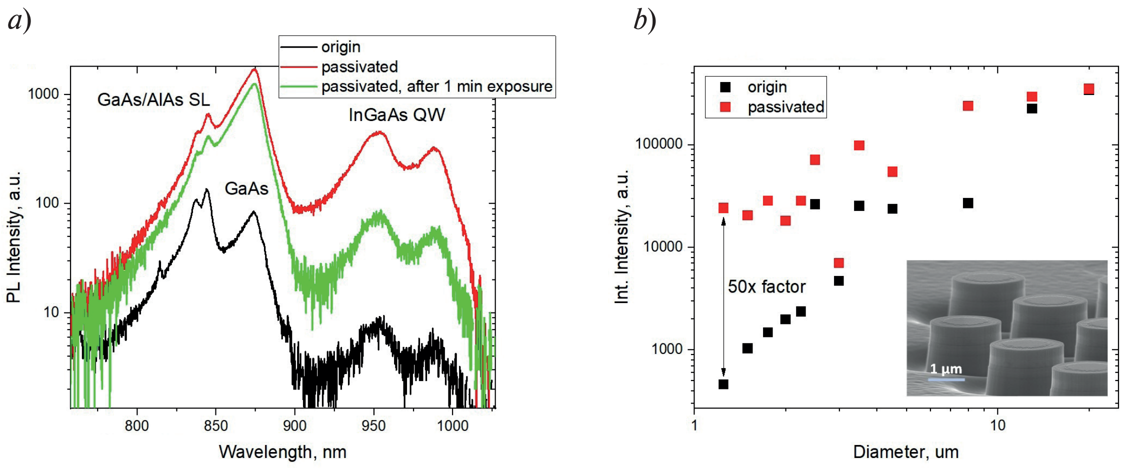

Fig. 2. PL spectra before and after passivation for sample №2 with 1.25 μm diameter mesas (*a*). Integrated PL intensity for different mesas diameter of sample №2 (*b*)

a diameter of 1.25 μm). The reason for much lower PL enhancement of SL signal may be that AlAs is much more sensitive to moisture and oxidation and can degrade or form unstable oxides that are not eliminated by passivation.

Fig. 2, *b* shows the integral PL intensity of the studied arrays of mesa structures of different diameters for sample №2. The greatest enhancement of the integral PL intensity is observed for mesostructures with a diameter of 1.25 μm. As the mesa's diameter increases, the contribution of nonradiative recombination to the PL signal decreases, leading to the most significant passivation effect being observed for small mesas with diameters of 1.25–3 μm in diameter. Thus, further mesas's diameter increment does not lead to enhancement of PL signal. This dependence also can be attributed to the diffusion length of charge carriers in InGaAs/GaAs quantum wells, which is on the order of 2–3 μm [5].

Conclusion

For the first time the effect of surface passivation of GaAs mesa structures with active region on the basis of InGaAs/GaAs QW using SiO_2 layer obtained by sol-gel method was investigated. Investigated PL intensity from the InGaAs/GaAs QW was significantly enhanced after SiO_2 passivation by sol-gel method. For sample №1 a maximum increase in the integrated intensity of 8 times was observed for the 2 and 3 μm diameter mesa structures. For sample №2 the maximum PL signal enhancement was 50 times for the diameter of 1.25 μm structures. The obtained results are promising for usage in microlasers with active region based on InGaAs/GaAs quantum wells.

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Received 27.08.2025. Approved after reviewing 02.09.2025. Accepted 03.09.2025.