Conference materials
UDC 538.9
DOI: https://doi.org/10.18721/JPM.183.207

Effect of rapid thermal annealing on the properties of GaPN(As)-based heterostructures grown on silicon substrates

S.N. Khrul[1]✉, K.Yu. Shubina[1], E.V. Pirogov[1], A.K. Kaveev[2], E.V. Nikitina[1,2]

[1] Alferov University, St. Petersburg, Russia;

[2] Ioffe Institute, St. Petersburg, Russia

✉ sonyahrul545@gmail.com

Abstract. The unique properties of dilute nitrides, such as GaPN(As), make them highly promising for use in solar cells and optoelectronic devices. In this work we report on the investigation of the effects of rapid thermal annealing on the structural and optical properties of GaPN(As) solid solutions. The GaPN(As)-based heterostructures were grown on a silicon substrates by plasma assisted molecular beam epitaxy. The effect of rapid thermal annealing on the properties of these materials was studied using photoluminescence spectroscopy and X-ray diffraction analysis.

Keywords: dilute nitride semiconductors, GaPN(As), rapid thermal annealing, photoluminescence, X-ray diffraction

Funding: This study was funded by RSCF (grant number 23-79-00032).

Citation: Khrul S.N., Shubina K.Yu., Pirogov E.V., Kaveev A.K., Nikitina E.V., Effect of rapid thermal annealing on the properties of GaPN(As)-based heterostructures grown on silicon substrates, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 18 (3.2) (2025) 45–48. DOI: https://doi.org/10.18721/JPM.183.207

Материалы конференции
УДК 538.9
DOI: https://doi.org/10.18721/JPM.183.207

Влияние быстрого термического отжига на свойства структур GaPN(As), выращенных на кремниевых подложках

С.Н. Хруль[1]✉, К.Ю. Шубина[1], Е.В. Пирогов[1], А.К. Кавеев[2], Е.В. Никитина[1,2]

[1] Академический университет им. Ж.И. Алфёрова РАН, Санкт-Петербург, Россия;

[2] Физико-технический институт им. А.Ф. Иоффе РАН, Санкт-Петербург, Россия

✉ sonyahrul545@gmail.com

Аннотация. Уникальные свойства разбавленных нитридов, таких как GaPN(As), делают их перспективными для использования в солнечных элементах и оптоэлектронных приборах. В данной работе мы исследуем влияние быстрого термического отжига на структурные и оптические свойства твердых растворов GaPN(As). Гетероструктуры GaPN(As) были выращены на кремниевых подложках методом молекулярно-пучковой эпитаксии с плазменной активацией. Влияние быстрого термического отжига на свойства этих материалов было изучено с помощью фотолюминесцентной спектроскопии и рентгеноструктурного анализа.

Ключевые слова: разбавленные нитриды, GaPN(As), быстрый термический отжиг, фотолюминесценция, рентгеновская дифракция

Финансирование: Исследование выполнено за счет гранта Российского научного фонда № 23-79-00032.

Ссылка при цитировании: Хруль С.Н., Шубина К.Ю., Пирогов Е.В., Кавеев А.К., Никитина Е.В. Влияние быстрого термического отжига на свойства структур GaPN(As), выращенных на кремниевых подложках // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2025. Т. 18. № 3.2. С. 45–48. DOI: https://doi.org/10.18721/JPM.183.207

Introduction

Dilute nitrides are a class of III-V semiconductors in which a small fraction of the group V atoms is replaced by nitrogen. Low-nitrogen solid solutions, such as GaPN(As), show unique properties, including direct and variable bandgap on the condition of lattice matching with silicon substrates [1]. Thus, these materials have the potential for creating efficient light-emitting devices for integrated silicon photonics.

It is known that heteroepitaxy on Si substrates leads to the formation of many defects in GaPN(As)-based structures [2]. This in turn leads to degradation in their optical properties. At the same time, many studies have shown that the optical properties of GaPN(As) alloys can be improved if the density of defects is reduced. It can be achieved by optimizing the growth conditions or by performing post-growth rapid thermal annealing [2–5].

Materials and methods

In this study, a heterostructures with bulk GaPN(As) layer were grown by plasma assisted molecular beam epitaxy on a silicon substrate with a (001) orientation misoriented by 4°. We investigated three samples: 1, $GaP_{0.98}N_{0.02}$/Si with a bulk layer thickness of 300 nm; 2, $GaP_{0.98}N_{0.02}$/Si with a bulk layer thickness of 600 nm; 3, $GaP_{0.88}N_{0.02}As_{0.1}$/Si with a bulk layer thickness of 1200 nm.

After growth, the samples were annealed at temperatures of 830, 850 and 870 °C for 30 seconds on a Jipelec JetFirst 100 setup in a nitrogen atmosphere. The optical properties of heterostructures before and after annealing were studied by photoluminescence (PL) spectroscopy in the range of 550–700 nm at room temperature. The structural properties were assessed by X-ray diffraction analysis using an X-ray diffractometer DRON-8 (with the copper anode with radiation type Kα1 (λ = 1.5405 Å).

Results and discussion

The PL spectra of the first and second samples before and after rapid thermal annealing (RTA) are presented in Fig. 1, *a, c*. The peak PL intensity of the sample 1 after annealing increases about two times at temperatures of 830 and 850 °C and has not changed at 870 °C. The peak PL intenаsity of the sample 2 after annealing increases about two times at temperatures of 830 and 870 °C and about three times at 850 °C. So, the maximum PL intensity was obtained at a temperature of 830 °C for sample 1 and 850 °C for sample 2. In addition to the intensity increase, a shift of the peak wavelength to the short-wave region of the spectrum (blueshift) was observed with increasing annealing temperature. More details of the changes in the photoluminescence peak for sample 1 and 2 are shown in Fig. 1, *b, d*.

The increase in PL intensity may be due to the density of N-related point defects is reduced by RTA [3]. The blueshift could be caused by the increase in injected carriers due to the decrease of defects and the improvement of the uniformity of the nitrogen compositions after annealing [6]. At annealing temperatures of 850 and 870 °C peaks corresponding to different composition of GaPN appear. This indicates splitting of homogeneous composition of GaPN into regions with different concentration of nitrogen.

The third sample's intensity doubled after annealing at 830 °C and increased by one and a half times after annealing at 850 and 870 °C (Fig. 2, *a*). For the last two temperatures extra bends of the PL curve appear, as it was in the case of the second sample, indicating the presence of different nitrogen clusters.

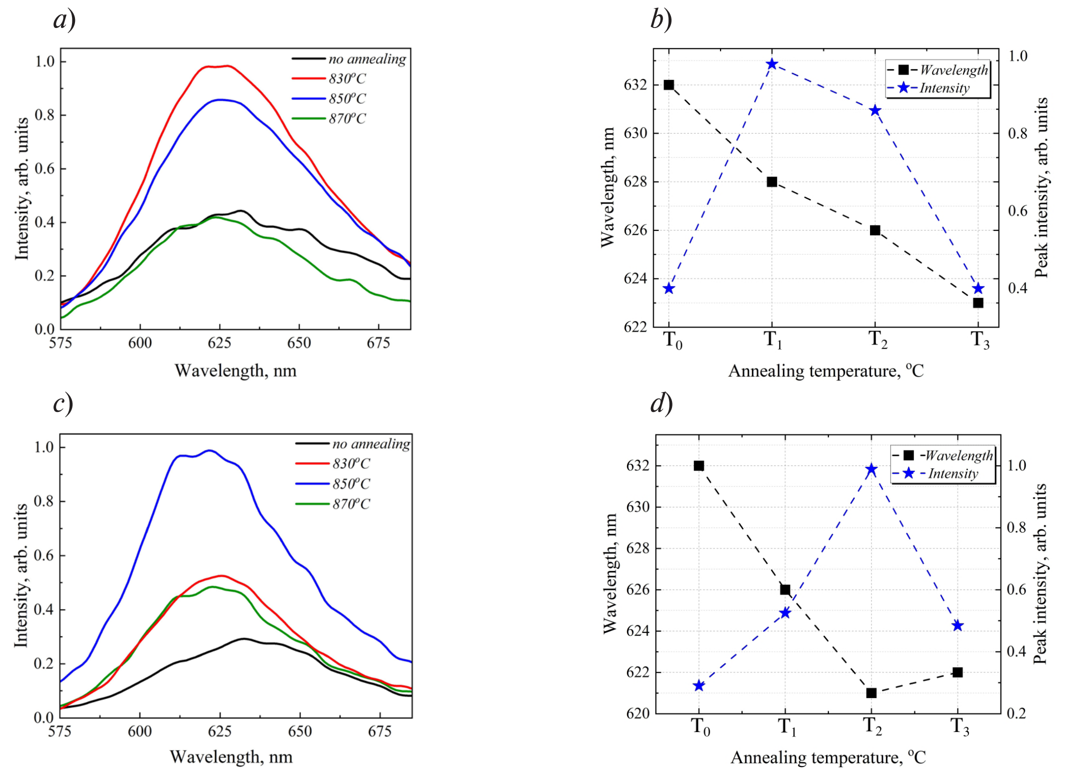

Fig. 1. PL spectrum of samples 1 (*a*) and 2 (*c*) without annealing and after RTA at different temperatures; dependence of peak PL intensity on annealing temperature (blue stars) and wavelength on annealing temperature (black squares) of samples 1 (*b*) and 2 (*d*), where T_0 corresponds to no annealing, T_1, T_2, T_3 to 830, 850, 870 °C, respectively

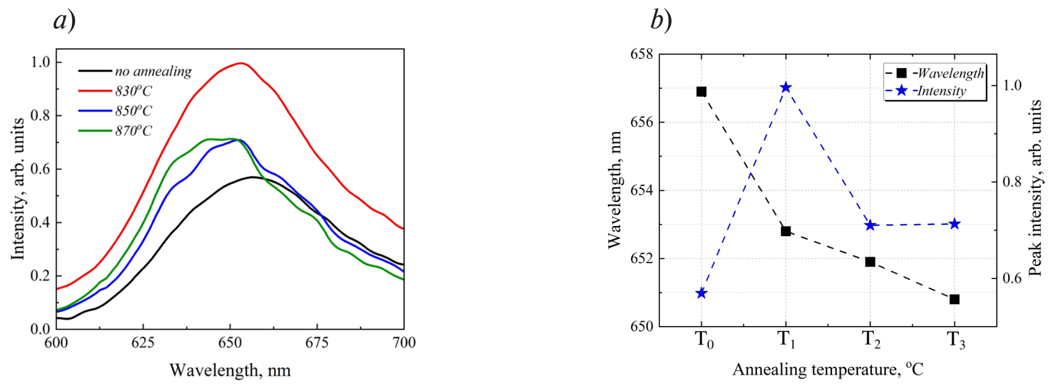

Fig. 2. PL spectrum of the sample 3 without annealing and after RTA at different temperatures (*a*); dependence of peak PL intensity on annealing temperature (blue stars) and wavelength on annealing temperature (black squares), where T_0 corresponds to no annealing, T_1, T_2, T_3 to 830, 850, 870 °C, respectively (*b*)

At the same time, the X-ray diffraction pattern shows that the crystal structure of the bulk layer remained unchanged, that is the XRD curve shape does not depend on the annealing temperature (Fig. 3).

A slight shift in the peak of the buffer layer is also observed. Shift to the right is due to stress relaxation in the buffer layer, since number of defects decreases after annealing.

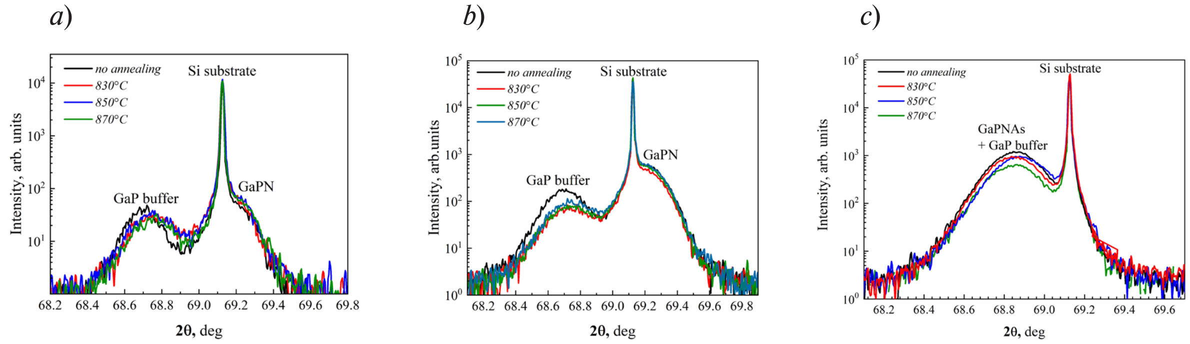

Fig. 3. XRD curves without annealing and at different annealing temperatures of sample 1 (*a*); sample 2 (*b*); sample 3 (*c*)

Conclusion

We have studied the effects of rapid thermal annealing on the optical and structural properties of GaPN(As) layers grown on a silicon substrate by plasma assisted molecular beam epitaxy. It was shown that the rapid thermal annealing process at 830–870 °C for 30 s in N_2 atmosphere successfully improves, as expected, the PL intensity of the GaPN layers about two and three times and the GaPNAs layer about two times. In addition, the optimal annealing temperature of samples was found (830 and 850 °C). At the same time, a decrease in the density of defects was observed and no changes in the structural properties of the bulk layers GaPN(As) were observed after RTA.

REFERENCES

1. **Mohamed Henini,** Dilute Nitride Semiconductors, 1st Edition, Elsevier Science. (2004).
2. **Ben Saddik K., et al.,** Growth modes and chemical-phase separation in $GaP_{1-x}N_x$ layers grown by chemical beam epitaxy on GaP/Si (001), J. Appl. Phys. 134 (2023) 175703.
3. **Balanta M.A.G., et al.,** Effects of nitrogen incorporation and thermal annealing on the optical and spin properties of GaPN dilute nitride alloys, Journal of Alloys and Compounds. 814 (2020) 152233.
4. **Lazarenko A.A., Shubina K.Yu., Nikitina E.V., et al.,** Influence of rapid thermal annealing on the distribution of nitrogen atoms in GaAsN/GaAs, Ioffe Institute Journal: Physics and technique of semiconductors. 55 (11) (2021) 1080–1077.
5. **Sakuntam Sanorpima et al.,** Growth and post-growth rapid thermal annealing of InGaPN on GaP grown by metalorganic vapor phase epitaxy, Journal of Crystal Growth. 298 (2007) 150–153.
6. **Utsumi A., et al.,** Increase in luminescence efficiency of GaPN layers by thermal annealing, Physica Status Solidi. 7 (2003) 2741–2744.

THE AUTHORS

KHRUL Sofia N.
sonyahrul545@gmail.com
ORCID: 0009-0007-6952-4987

KAVEEV Andrey K.
kaveev@mail.ioffe.ru
ORCID: 0000-0002-3640-677X

SHUBINA Kseniia Yu.
rein.raus.2010@gmail.com
ORCID: 0000-0003-1835-1629

NIKITINA Ekaterina V.
mail.nikitina@mail.ru
ORCID: 0000-0002-6800-9218

PIROGOV Evgeny V.
zzzavr@gmail.com
ORCID: 0000-0001-7186-3768

Received 06.09.2025. Approved after reviewing 11.09.2025. Accepted 29.09.2025.