Conference materials
UDC 538.958
DOI: https://doi.org/10.18721/JPM.153.351

Optical studies of InP nanostructures monolithically integrated in Si (100)

I. A. Melnichenko [1]✉, N. V. Kryzhanovskaya [1], Yu. S. Berdnikov [1, 2], E. I. Moiseev [1], I. S. Makhov [1]

[1] Higher School of Economics University, St. Petersburg, Russia;

[2] St. Petersburg State University, St. Petersburg, Russia

✉ imelnichenko@hse.ru

Abstract. We present a photoluminescence study of InP nanostructures monolithically integrated to Si (100) substrate. The InP nanostructures were grown in pre-formed pits in the silicon substrate using an original approach by metal–organic vapor phase epitaxy via selective area growth driven by molten alloy. The obtained InP/Si nanostructures have submicron size above and below substrate surface. InP nanostructures were investigated by photoluminescence spectroscopy at temperatures in the range of 5–300 K and at different pump power. Room temperature photoluminescence spectra of the studied structures exhibit the peak corresponding to zinc blende InP band gap. The obtained results show high crystalline quality of the InP material.

Keywords: III-V nanostructures, InP monolithically integrated on silicon, near IR radiation

Funding: This study was supported by Russian Science Foundation grant No. 22-22-20057, https://rscf.ru/project/22-22-20057/ and by St. Petersburg Science Foundation grant 66/2022 dated 15 April 2022.

Citation: Melnichenko I. A., Kryzhanovskaya N. V., Berdnikov Yu. S., Moiseev E. I., Markov I. S., Optical studies of InP nanostructures monolithically integrated in Si (100). St. Petersburg State Polytechnical University Journal. Physics and Mathematics, 15 (3.3) (2022) 260–264. DOI: https://doi.org/10.18721/JPM.153.351

Материалы конференции
УДК 538.958
DOI: https://doi.org/10.18721/JPM.153.351

Изучение оптических характристик INP нановключений интегрированных на Si (100)

И. А. Мельниченко [1]✉, Н. В. Крыжановская [1], Ю. С. Бердников [1, 2], Э. И. Моисеев [1], И. С. Махов [1]

[1] Национальный исследовательский университет «Высшая школа экономики», Санкт-Петербург, Россия;

[2] Санкт-Петербургский государственный университет, Санкт-Петербург, Россия

✉ imelnichenko@hse.ru

Аннотация. Мы представляем исследование фотолюминесценции нановключений InP, монолитно интегрированных в подложку Si (100). Нановключения InP были выращены в предварительно сформированных отверстиях в кремниевой подложке с использованием нового подхода, основанного на селективном росте и капельном осаждении на базе метода металлоорганической газофазной эпитаксии. Отдельные нановключения InP/Si были исследованы методом спектроскопии фотолюминесценции в диапазоне температур 5–300 K при различной мощности накачки. Спектры фотолюминесценции исследованных структур при комнатной температуре демонстрируют максимум интенсивности, соответствующий ширине запрещенной зоны InP в конфигурации

сфалерита. Полученные результаты свидетельствуют о высоком кристаллическом качестве нановключений InP.

Ключевые слова: III-V наноструктуры, интеграция InP на кремний, излучение в ближнем ИК диапазоне

Финансирование: Работа выполнена при поддержке гранта РНФ № 22-22-20057, https://rscf.ru/project/22-22-20057/ и гранта Санкт-Петербургского научного фонда в соответствии с соглашением от 15 апреля 2022 г. № 66/2022.

Ссылка при цитировании: Мельниченко И. А., Крыжановская Н. В., Бердников Ю. С., Моисеев Э. И., Махов И. С. Изучение оптических характристик InP нановключений, интегрированных на Si (100) // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2022. Т. 15. № 3.3. С. 260–264. DOI: https://doi.org/10.18721/JPM.153.351

Introduction

Seamless integration of optically active A3B5 materials on silicon is the key challenge in creation of integrated light sources, which are highly demanded for further development of quantum computing, communications, and sensing [1, 2]. Compatibility with the well-developed silicon-based fabrication is crucial for scalability of new generation of compact and power- efficient light sources [3, 4]. The desired structures therefore can combine A3B5 materials (with high electron mobility and direct band gap) and the highly optimized processing of Si (001) platform.

However, integration the III-V-based light emitting devices with Si substrates is difficult because of the lattice mismatch between most of A3B5 materials and silicon, as well as the difference in polarity and thermal expansion coefficients, which typically lead to high defect density in the structures. Meanwhile, low number of defects and dislocations is critical for optical devices due to the detrimental impact of non-radiative recombination of charge carriers on the efficiency of light emission.

In this work we study InP nanostructures epitaxially grown in the pits of Si (100) substrates using the recently developed method of selective area metal–organic vapor phase epitaxy (MOVPE) driven by molten alloy, which allows obtaining InP/Si nanostructures with low crystal defect density and sharp interfaces between the grown InP and hosting Si [5]. Here we study the optical properties of the formed InP/Si nanostructures using microphotoluminescence (PL) measurements correlated with scanning electron microscopy and surface mapping by confocal microscopy.

Materials and Methods

Nanostructure fabrication started with the deposition of SiN_x mask on top of Si (100) surface and formation of the array of 200 nm wide openings in the mask spaced 800 nm apart each other. Then, the inverted-pyramidal pits in Si were etched within the mask openings using KOH aqueous solution. The substrate patterning was followed by deposition of the droplets of indium-rich melt inside the etched pits, which is then was annealed in phosphine (PH_3). The structures with the optimal crystal quality formation were obtained after annealing under PH_3 flux of $2.2 \cdot 10^{-2}$ mol min^{-1} and substrate temperature of 600 °C More details of the fabrication procedure can be found in [5].

PL maps and spectra were measured using an Integra Spectra NT-MDT confocal microscope at room temperature. The Nd:YLF laser operating in continuous mode (527 nm wavelength) was used for excitation. The excitation laser beam was focused using a 100x objective (Mitutoyo, M Plan APO NIR) with a numerical aperture NA = 0.5. The same objective was used to collect the photoluminescence signal of InP nanostructures. The radiation was directed to the entrance slits of the monochromator (Sol Instruments MS5204i) using mirrors. Detection was performed using a cooled InGaAs CCD array (iDus). To acquire the PL spectra at low temperatures, the structures were placed into the closed-cycle helium cryostation Montana Instruments Cryostation s50.

Results and Discussion

Fig. 1 shows typical spectra obtained from single InP nanostructure with a single peak at 915 nm (corresponding to InP in the zinc blende crystal phase) and the full width at half maximum (FWHM) of about 55 nm. SEM image of the array of InP nanostructures is also shown in the inset to Fig. 1.

The nanostructure marked with the red circle in the inset to Fig. 1 was also explored in depth. PL scanning over the depth of this nanostructure was performed using mirror optics of the confocal microscope and tunable holder. Obtained results show the homogeneity of InP peak shape and a gradual decrease of PL intensity in the depth of the substrate. This decline in the PL intensity is related to the inverted pyramidal shape of the etched pits which implies the reduction of InP volume with the depth.

Photoluminescence at room temperature is observed from almost every single nanostructure, indicating the formation of InP crystals without threading dislocations. Also, we observed significant variation of the PL intensity from different nanostructures, that may be due to the different amount of InP material inside the pits and. Meanwhile the spectra have similar shape and position of the peak.

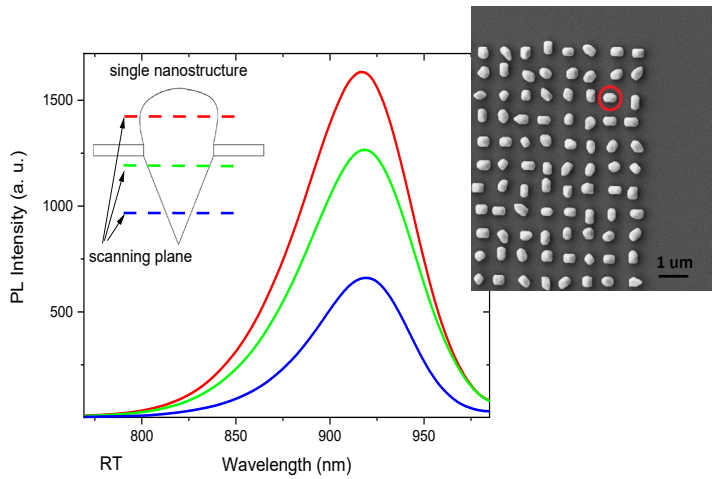

Fig. 1. PL spectrum from highlighted InP nanostructure, measured at room temperature over the depth. SEM image on inset

Next, we studied low temperature photoluminescence spectra of the nanostructure (Fig. 2). At 5 K we observe three spectral lines assigned to zinc blende InP free exciton (FE) at 1.417 eV, bound exciton (BE) at 1.412 eV and donor-valence band transition (1.404 eV) [6]. As temperature rising, the high energy processes increase. The donor-valence band line disappears at ~ 20 K and the bound exciton line does at ~ 30 K. As the temperature is increased further, the intensity of free exciton band emission increases and dominates the spectrum.

Most of the scanned nanostructures have similar low-temperature spectra in wavelength range of 870–900 nm. In contrast, the shorter-wavelength series of lines (840–860 nm or 1.48–1.44 eV) have different intensity and wavelengths in each nanostructure. These lines are probably caused by twinning defects in InP/Si nanostructures that were observed by transmission electron microscopy [5].

Twins are often found in III-V nanostructures and can be considered as monolayer phase of wurtzite (WZ) in zinc blende (ZB) material. This kind of defects does not form dangling bonds and thus not affect drastically the intensity of radiative recombination. The existence of heterointerfaces due to ZB/WZ polytypism causes the appearance of type II band alignment. The contribution from recombination on the type II band transitions can be observed in the long decay of shortwave tail, shown in figure 3 [7]. Thus, high energy PL lines at low temperatures (Fig. 2) may be caused by appearance of wurtzite InP phase (1.486 eV). Nevertheless, these lines have very low intensity and even disappear in some studied nanostructures, so we can conclude that the most of nanostructures have a zinc blende structure of high crystalline quality.

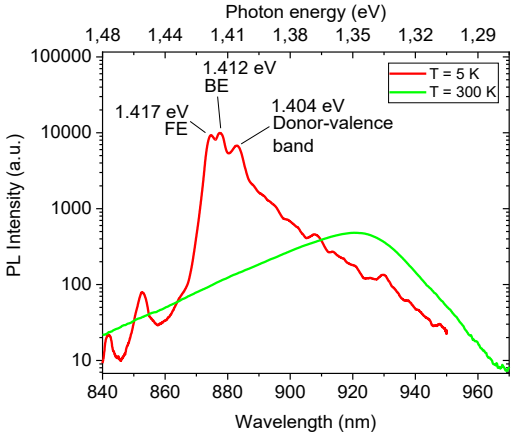

Fig. 2. PL spectra of single InP nanostructure, measured at 5K and room temperature

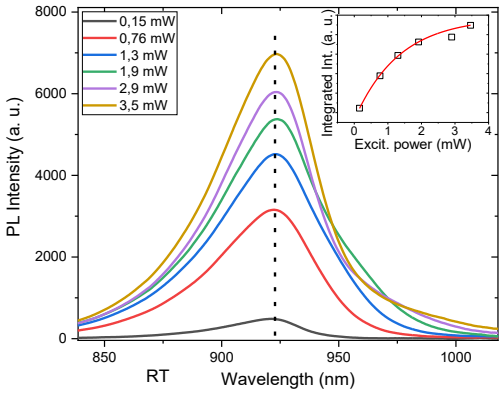

Fig. 3. Dependence of InP nanostructure PL intensity on pumping power

Fig. 3 illustrates the variation of room temperature PL intensity with the excitation power. With the pump power increase from 0.15 to 3.5 mW the FWHM of the PL peak increases from 37 nm (55 meV) to 50 nm (73.5 meV). The peak wavelength remains nearly constant and only shifts slightly to the longer wavelengths at high excitation power due to the structure heating. The shape of the peak (the long wavelength tail) strongly depends on the position on the sample, the crystal quality of individual InP structures. Slowdown of integral intensity growth with the pump power can be fitted with an exponential function. Such behavior can be explained by the saturation of radiative recombination in the volume of a single nanostructure.

Conclusion

We investigated the optical properties of the InP nanostructures monolithically integrated into Si (100) synthesized via this original epitaxial method. Obtained InP nanostructures show PL emission in the near-infrared range (PL peak at ~ 920 nm) at room temperature. Their intensity varies from each other due to different volume of InP. PL scanning over the depth of nanostructures shows the homogeneity of InP peak and a gradual decrease of PL intensity with depth. Low temperature measurements showed spectral lines assigned to zinc blende InP transitions and low peaks in shorter wavelengths, that can be associated with twinning defects in InP nanostructures. The obtained results demonstrate high crystalline quality of the integrated InP zinc blende nanostructures and their optical characteristics.

Acknowledgments

The authors are thankful to E. Semenova and D. Viazmitinov for the provided structures.

REFERENCES

1. **Liu S., Khope A.,** Latest advances in high-performance light sources and optical amplifiers on silicon, Journal of Semiconductors 42 (2021) 041307.

2. **Sun K., Gao J., Jung D., Bowers J., Beling A.,** 40 Gbit/s waveguide photodiode using III–V on silicon heteroepitaxy, Optics Letters. 45 (11) (2020) 2954–2956.

3. **Bettotti P.,** Hybrid materials for integrated photonics. Advances in Optics. 2014 (2014).

4. **Roelkens G., Abassi A., Cardile P., Dave U., De Groote A., De Koninck Y.,** Van Thourhout D., et al., III-V-on-silicon photonic devices for optical communication and sensing, In Photonics, Multidisciplinary Digital Publishing Institute. 2 (3) (2015) 969–1004.

5. **Viazmitinov D. V., Berdnikov Y., Kadkhodazadeh S., Dragunova A., Sibirev N., Kryzhanovskaya N. V., Radko I., Huck A., Yvind K., Semenova E.,** Monolithic integration of InP on Si by molten alloy driven selective area epitaxial growth, Nanoscale. 12 (46) (2020) 23780–23788.

6. **Heim U., Röder O., Queisser H. J., Pilkuhn M.,** Photoluminescence of InP, Journal of Luminescence. 1 (1970) 542–551.

7. **Alouane M. H., Chauvin N., Khmissi H., Naji K., Ilahi B., Maaref H., Bru-Chevallier C.,** Excitonic properties of wurtzite InP nanowires grown on silicon substrate, Nanotechnology. 24 (3) (2012) 035704.

THE AUTHORS

MELNICHENKO Ivan A.
imelnichenko@hse.ru
ORCID: 0000-0003-3542-6776

MOISEEV Eduard I.
emoiseev@hse.ru
ORCID: 0000-0003-3686-935X

KRYZHANOVSKAYA Natalia V.
nataliakryzh@gmail.com
ORCID: 0000-0002-4945-9803

MAKHOV Ivan S.
makhoviv@gmail.com
ORCID: 0000-0003-4527-1958

BERDNIKOV Yury S.
yuryberdnikov@gmail.com
ORCID: 0000-0002-1630-1559

Received 13.07.2022. Approved after reviewing 21.07.2022. Accepted 22.07.2022.