St. Petersburg Polytechnic University Journal. Physics and Mathematics. 2024. Vol. 17. No. 3.1
Научно-технические ведомости СПбГПУ. Физико-математические науки. 17 (3.1) 2024

Conference materials
UDC 535.3
DOI: https://doi.org/10.18721/JPM.173.122

Numerical modal analysis of GaP optical microcavity

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Abstract. Despite the highly developed level of the silicon technology, efficiency of silicon-based photon devices is limited by material properties. In contrast, III-V materials are mostly applicable to make such type of devices as well as fabricating them in nanowire (NW) form provides compatibility with silicon technology. GaP(NAs) is a useful material system for optoelectronics because of tunable bandgap with controllable directivity and high refractive index. The eigenmodes of the Fabry-Perot resonator based on GaP NWs have been investigated. The simulation results showed that raise in diameter leads to the increase in the number of optical modes having different light distribution due to transverse mode type. Quality factor analysis shows growth in its values with the increase in structures' diameters.

Keywords: nanowires, gallium phosphide, Fabry-Perot resonance, waveguide modes

Funding: This study was funded by the Ministry of Science and Higher Education grant number FSEG-2024-0017.

Citation: Funtikova A.S., Mozharov A.M., Fedorov V.V., Sharov V.A., Mukhin I.S., Numerical modal analysis of GaP optical microcavity, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 17 (3.1) (2024) 115–119. DOI: https://doi.org/10.18721/JPM.173.122

Материалы конференции
УДК 535.3
DOI: https://doi.org/10.18721/JPM.173.122

Модовый анализ оптических микрорезонаторов GaP

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Аннотация. Несмотря на высокий уровень развития кремниевой технологии, эффективность фотонных устройств на основе кремния ограничена свойствами материала. Материалы группы III-V более применимы для создания устройств такого типа, а их изготовление в форме нитевидных нанокристаллов (ННК) обеспечивает совместимость с кремниевой технологией. GaP(NAs), благодаря перестраиваемой запрещенной зоне и высокому показателю преломления, является перспективной системой для оптоэлектроники. В работе был исследован модовый состав резонатора Фабри-Перо на основе ННК GaP. Результаты моделирования показали, что увеличение диаметра приводит к росту числа оптических мод с различным распределением света за счет поперечного типа моды. Анализ коэффициента добротности показывает рост его значений с увеличением диаметра структур.

Ключевые слова: нитевидные нанокристаллы, фосфид галлия, резонанс Фабри-Перо, волноводные моды

Финансирование: Работа выполнена при финансовой поддержке Министерства науки и высшего образования (грант государственного задания FSEG-2024-0017).

Ссылка при цитировании: Фунтикова А.С., Можаров А.М., Федоров В.В., Шаров В.А., Мухин И.С. Модовый анализ оптических микрорезонаторов GaP // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2024. Т. 17. № 3.1. С. 115–119. DOI: https://doi.org/10.18721/JPM.173.122

Introduction

Increase in the amount of transmitted information leads to enhancing data transfer speed which requires new technological and conceptual solutions for transmissive circuits. One of the promising approaches to achieve high-speed on-chip systems is based on using integrated optics instead of metal conductors. Passive optical elements can be made with well-known silicon technology, but it requires not only special IR light sources, but IR detectors. On the other hand to employ Si detectors SiNx technology can be used to work in visible or near IR spectrum range, but its low refractive index limits minimal size of photonic elements not to mention the requirement of light sources.

Other perspective materials are III-V semiconductors, including gallium phosphide. Good quality crystals can be grown on Si substrate due to the good lattice matching. High refractive index [1] and transparency in wide visible and infrared range [2], thus, small optical losses in this part of the spectrum, make GaP structures very promising for use in photonic integrated circuits. In general, gallium phosphide has indirect band gap, but it is possible to make it direct with As and N doping [3], which make them interesting not only for passive circuits' elements, but also active, such as lasers, light-emitting diodes, waveguides and nanoantennas. But in case of small sized light sources the planar technology approves oneself unfit due to required etching that leads to the appearance of free lateral surface, which can cause additional losses and reduce efficiency.

The solution can be III-V nanowires (NWs). They demonstrate high crystallinity and can also be grown on Si substrate, so, can be compatible with silicon technology [4] and efficiently used in nanophotonics due to their size. NWs lateral surfaces that have mirror-like quality also can be passivated by growing core-shell structures. It is important to mention that selective area growth methods can be used for element's construction in a predetermined location and solve the problem of placing and adjusting light sources with passive elements.

In optical integrated photonics, precise control over the direction of light distribution and mode structure is crucial for achieving high performance and functionality in photonic devices. This control affects several important aspects of photonics, including signal integrity, wavelength-division multiplexing, interconnect efficiency, and the performance of optical sensors. Selection of NWs parameters can help in optical alignment with other elements. Effective management of light paths improves signal routing, multichannel processing capabilities, and the ability to integrate complex functions into smaller chip areas. This enhances the development of compact, fast, and energy-efficient optical systems.

In this work numerical modal analysis of different size microcavities based on GaP NWs was done. The main goal of the work was to obtain correlation between NW size, wavelength and the NW's optical modal structure to specify optimal conditions for use GaP(NAs) NW as a small size optical source for integrated photonic circuits.

Materials and Methods

In our study COMSOL Multiphysics was used to simulate the necessary phenomenon. The MUMPS (multifrontal massively parallel sparse direct solver) was used to obtain the solutions. Also we use parametric sweeps to change diameter and length of the structure to analyze all necessary configurations. To get rid of any interference phenomena, a perfect matched layer (PML) on external boundaries was used. Refractive and extinction indexes for GaP, used for our calculations, were taken from [5]. Environment was declared as air with refractive index $n = 1$ and no extinction.

Results and Discussion

Due to the high refractive index and atomically smooth surfaces GaP NWs are able to localize electromagnetic waves and act as a resonator. NW's geometry has high asymmetry and, in consideration with general oscillations theory, one can expect a high level separation of the modal structure into groups, where the behavior within and between groups corresponds to a change in the order of resonance along or across the NW axis. Resonance appearance in the system caused by the fulfillment of the constructive interference conditions. Numerically it means that the product of wave vector and geometrical size of the system must equals defined discrete values. Wave vector in turn usually has an unknown value, and for system characterization a new parameter with close physical meaning is convenient in use. This parameter represents the ratio between geometrical size and wavelength. For the considered system a numerical calculation of modal structure was held and quality factor dependence on the size parameter $x = d/\lambda$ (d is NW diameter, λ is operating wavelength), which is shown on (Fig. 1, *a*), was built. Each point on this graph represents a resonance.

It can be seen that the increase in size parameter (this corresponds to rise in NW diameters or usage of more short-wave light) leads to the appearance of higher order resonant modes. Such stepwise nature of the dependence can be explained with the distribution possibility of resonant modes of different transverse order. Since increasing the x parameter the transverse

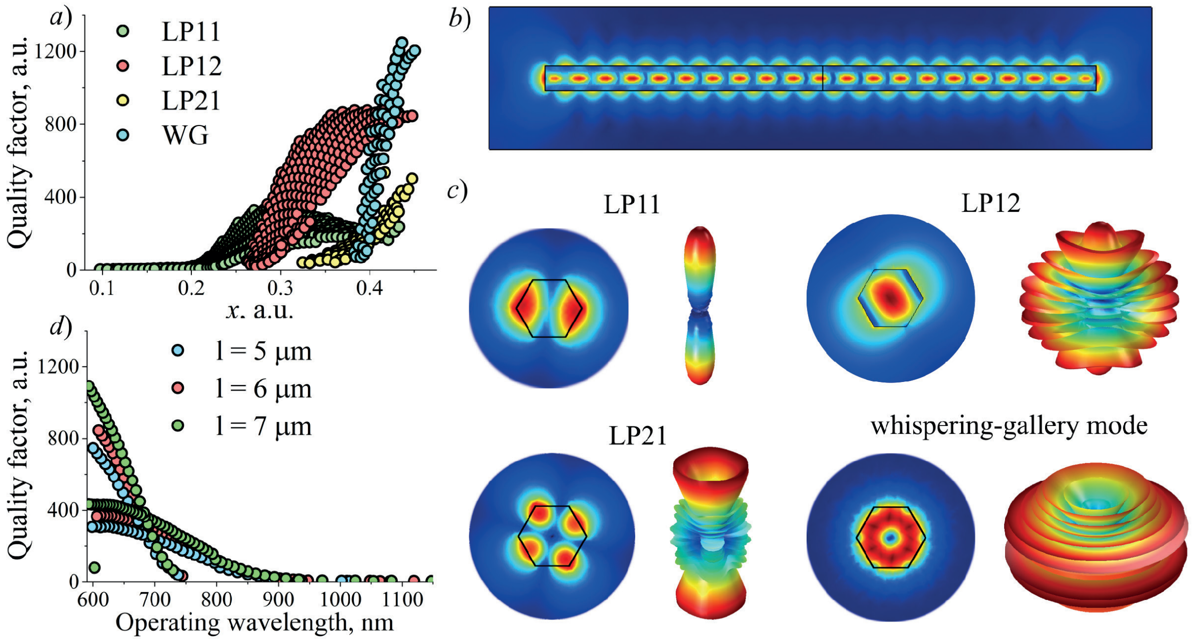

Fig. 1. Q-factor dependence on size parameters (NW length is 5 µm) for different modes in GaP NWs (*a*). Typical electric field distribution along the structure (*b*). Electric field distribution across the NW and far fields for some first transverse modes (*c*). Q-factor dependence on NW lengths (d = 200 nm) for different modes in GaP NWs (*d*)

wave vector increases too. It leads to the achievement of the next constant, representing the fulfillment of the constructive interference conditions for the next higher order transverse resonance. Likewise, within each group resonances are related to the changes in constructive interference conditions along NW. Based on the type of electric field distribution along the NW (Fig. 1, *b*), it can be concluded that the establishment of resonance conditions is associated with reflection from the NW's end surfaces and interference of electromagnetic wave. This fact suggests that the longitudinal component of the wave vector is represented by Fabry-Pérot resonances. Meanwhile in contradiction with typical Fabry-Pérot resonances behaviour, there is no plane wave in NW cross section, but the set of the transverse field distribution patterns (Fig. 1, *c*). It is related to spatial limitations for the wave by NW lateral surfaces. Thorough analysis of the transverse field distribution patterns shows that the main resonances set in the range of $x < 0.39$ is presented with transverse to the NW axis electromagnetic waves with linear electric polarization of increasing from 1 to 2 radial and azimuthal order, which changes with rise in size parameter. However, beginning with some value ($x = 0.39$) high quality whispering-gallery modes with azimuthal order equal to 3 can be detected. Typical Fabry-Pérot resonances have only longitudinal component of the wave vector. But in the considered system transverse component also can be detected and it was necessary to study the direction of light distribution, so the far field for the GaP NW is represented (Fig. 1, *c*). One of typical characteristic features is clearly seen on the far field diagrams: the end faces of the NWs for Fabry-Pérot modes are the largest sources of losses. Here we can see that LP11 mode is more directed than others: this corresponds to the minimal value of the wave vector transverse component.

Initially, it was expected to observe on (Fig. 1, *a*) distinct curves corresponding to each possible mode; however, instead of discrete curves, the graph displays “zones”. These zones likely result from changes in the effective refractive index due to presence of the material dispersion. Growth of the q-factor with decrease in wavelength can be detected due to the rising of energy quantity that can stay in the resonator.

Also the dependence of q-factor on NW length was investigated (Fig. 1, *d*). Increase in NW length, as wavelength decreases, leads to growth in energy that can distribute in the resonator. But the end faces of the NW, which, as have been mentioned above, are the largest source of optical losses, don't increase in this process. These two reasons lead to the slight increase in modes' q-factor with rise in NW length.

Conclusion

We have demonstrated results of the numerical study of the GaP nanowires with different geometry configurations, which can fully describe the modal structure of these objects. The results of this calculation can be used for growing GaP NWs with known characteristics for integration into photonic circuits as lasers, light-emitting diodes, waveguides, etc.

Acknowledgments

The work was supported by the Ministry of Science and Higher Education (state assignment grant FSEG-2024-0017).

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Received 22.07.2024. Approved after reviewing 07.08.2024. Accepted 08.08.2024.