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Photoluminescence anisotropy in hybrid nanostructures based on gallium phosphide nanowire and 2D transition metal dichalcogenides

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Abstract. Integration of nanophotonic structures having different geometry is a well-established way to promote desired optical effects. This work is aimed at study of the optical properties of a hybrid structure based on a transition metal dichalcogenides (TMDC) thin layer and III-V nanowires. The structures were studied by μ-Raman and μ-photoluminescence spectroscopy at room temperature. We demonstrate experimentally guiding of the TMDC photoluminescence through the individual nanowires and analyze this phenomenon. The results of the work shed a light on new ways for fabrication of integrated optical circuitry components.

Keywords: photonics, photoluminescence, 2D TMDC, III—V semiconductors, nanowires

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Материалы конференции
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Анизотропия фотолюминесценции в гибридных наноструктурах на основе нитевидных нанокристаллов фосфида галлия и двумерных дихалькогенидов переходных металлов

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Аннотация. Создание гибридных наноструктур на основе матриалов с различной геометрией является одним из способов получения оптических элементов с заданными параметрами. Данная работа направлена на исследование оптических свойств гибридных структур на основе тонких слоев дихалькогенидов переходных металлов и нитевидных нанокристаллов фосфида галлия. Структуры исследовалась методами микроспектроскопии комбинационного рассеяния и фотолюминесценции. Благодаря совмещению излучательных свойств тонких слоев TMDC и волноводных свойств полупроводниковых ННК была получена анизотропная фотолюминесценция. Результаты работы могут быть использованы для изготовления компонентов интегральных оптических схем.

Ключевые слова: фотоника, фотолюминесценция, 2D TMDC, полупроводники А3Б5, нитевидные нанокристаллы

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Introduction

Thin layers of transition metal dichalcogenides (TMDCs) are a large family of two-dimensional materials with a number of unique physical properties. It is especially interesting that some of these materials exhibit an efficient photoluminescence in the visible and near-infrared ranges [1]. One of the problems limiting the usage of these materials for the development of devices is the low absorption capacity due to their small thickness [1]. It is possible to optimize absorption by using resonant optical structures [2]. Such structures include nanowires (NWs) of semiconductor compounds [3] providing several pathways for device applications [4, 5] including flexible devices

[6]. Due to the transparency and high refractive index [7] Gallium phosphide (GaP) NWs promote several peculiar effects [8, 9] promising for nanophotonic applications. It should be noted that these structures are able to support both resonant modes and waveguide modes [10], that makes them perfectly suitable for anisotropic signal outcoupling [11]. So, it becomes possible to fabricate nanoscale radiation sources for optical data processing on-chip systems. This work is focused on fabrication and study of the TMDC (molybdenum disulfide MoS_2 and molybdenum diselenide $MoSe_2$) and GaP NWs based hybrid structure for exploration of the field confinement and light guiding of the TMDC photoluminescence (PL).

Materials and Methods

Thin layers of TMDC were mechanically exfoliated from bulk crystals. GaP NWs were grown on a Si (111) substrate by molecular beam epitaxy using the vapor–liquid–solid mechanism according to the protocol reported previously [12].

The transfer of GaP NWs to TMDC layers was carried out via drop-cast technique: a small piece of the Si substrate with a vertical array of as-grown NWs was placed into Eppendorf tube filled with isopropanol and treated in an ultrasonic bath. A small volume of the suspension was dropped onto the Si/SiO_x substrate with thin TMDC layers. NWs were additionally positioned with an atomic force microscope (AFM) probe to achieve a desired geometry of the fabricated structure.

The structures were studied by μ-Raman and μ-photoluminescence (μ-PL) techniques at room temperature. The measurements were carried out on Horiba LabRAM HR 800 spectrometer equipped with confocal microscope with 100x magnification objective (N.A. = 0.9). Stage with piezoelectric controllers facilitated precise positioning of the laser beam, making it possible to measure PL maps with a high spatial resolution with a step of less than 100 nm. The excitation source was a 532-nm solid-state YAG:Nd continuous wave laser (455 μW) with diode pump. Scanning probe microscope Solver NEXT (NT-MDT) was used to obtain topography maps.

Results and Discussion

MoS_2 layer based hybrid structure. The optical image (Fig. 1,*a*) shows the obtained sample with the GaP NW and the thin MoS_2 layer. Intensity of the Raman signal is found uniform over the entire MoS_2 layer (Fig. 1,*f*). The shape of the gray area correlates with the optical image. It indicates that the thickness is homogeneous throughout the layer. The spectral distance between MoS_2 vibrational modes E^1_{2g} and A_{2g} on the Raman spectrum (Fig. 1,*k*) can be used to estimate a number of TMDC layers [13]. The spectral distance is found at 21.2 cm^{-1}, corresponding to the MoS_2 bilayer. The PL intensity map of the hybrid structure (Fig. 1,*c*) demonstrates the PL emission from the MoS_2 layer. The corresponding PL spectra (Fig. 1i) show two features: emission occurs as a result of direct A and B exciton transitions at the K point of the Brillouin zone according to the electronic band structure [14]. It should be noted, that a decrease in the PL signal is observed along the NWs lying on the MoS_2 layer (Fig. 1,*c*). This can be related to the field localization inside the NWs, which will be discussed in detail hereafter.

One of the NWs depicted in Fig. 1,*a* was moved with an AFM probe for a detailed study of the light propagation along it. The corresponding image of the final structure is depicted in Fig. 1,*b*. The diameter of the GaP nanowire was determined via analysis of AFM image and vary along its length (Fig. 1,*g*, *h*). The length of the NW is approximately 16.5 μm. The Raman integral intensity map of area 2 (Fig. 1,*e*) and Raman spectrum of the NW tip in area 2 (Fig. 1,*e*) with only GaP vibrational modes indicate that there are no TMDC layers under the NW at the top segments of the NW. However bright spots can be seen on the PL integral intensity map of area 2 (Fig. 1,*d*) obtained in the MoS_2 emission range (600–715 nm) manifesting the waveguiding promoted by GaP NWs reported earlier for various wavelengths [10, 15]. The thickness of NW promotes waveguiding for both the excitation radiation and PL signal, which is the response of the MoS_2 layer under the laser excitation. The PL spectrum of the transmitted signal (Fig. 1,*j*) correlates with the result shown in Fig. 1,*i*, which confirms the earlier suggestion about the waveguiding of the NW. The tip of the neighboring NW was moved only in area 1 (Fig. 1,*b*) as a `result of manipulating by the AFM probe. Therefore, the presence of the second spot on the PL integral intensity map of area 2 can be explained by the presence of an additional bundled NW optical coupled to the first one [16].

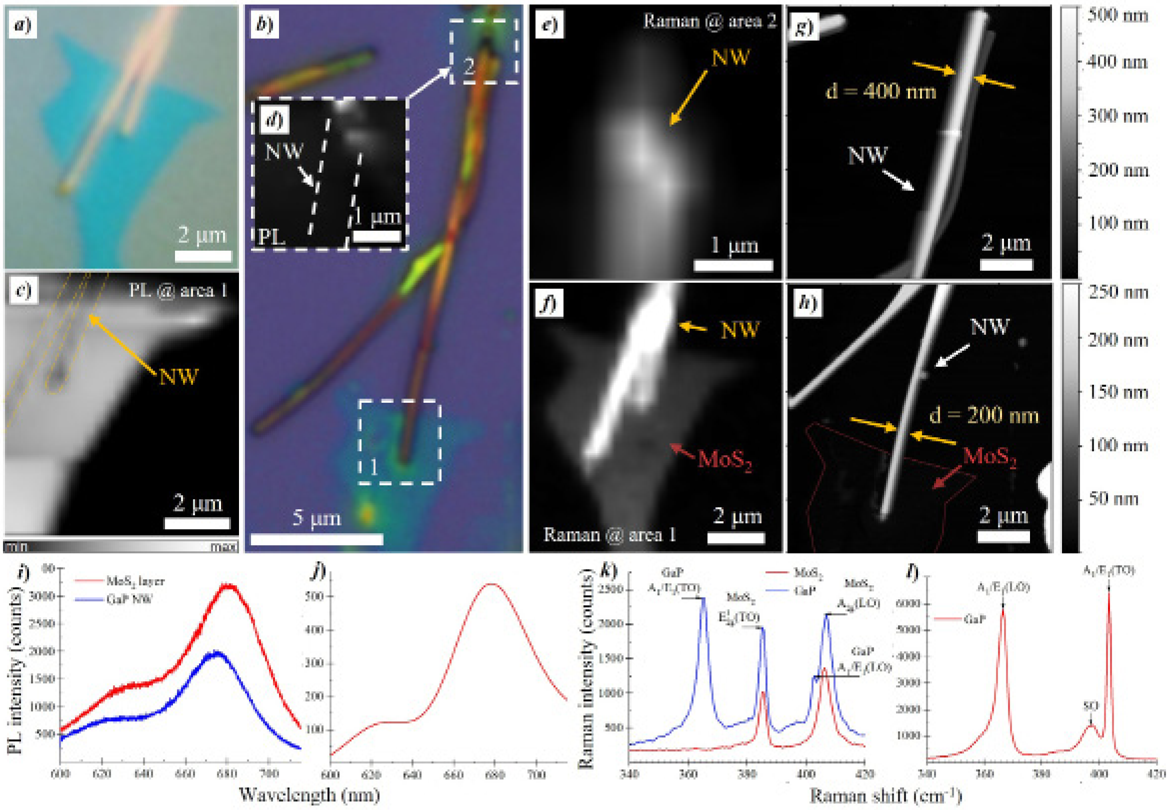

Fig. 1. Characterization of hybrid structures based on MoS_2 and GaP NWs: Optical image of the hybrid structure before (*a*) and after manipulation with the AFM probe (*b*); room temperature (RT) PL integral intensity maps of area 1 before manipulation with the AFM probe (*c*) and area 2 (*d*) in 600–715 nm range; RT Raman integral intensity maps of areas 2 (*e*) and 1 (*f*); AFM images of the upper (*g*) and lower (*h*) parts of the NW in 340–420 cm^{-1} range; PL spectra of the MoS_2 layer and GaP NW in area 1 (*i*); PL spectrum of the transmitted signal: with excitation at area 1, and signal collection in area 2 (*j*); Raman spectra of MoS_2 layer and GaP NW in area 1 (*k*) and NW tip in area 2 (*l*)

$MoSe_2$ layer based hybrid structure. A similar approach was proceeded to study hybrid structure with $MoSe_2$ layer and GaP NW. The optical and AFM images (Fig. 2,*a* and 2,*e*, respectively) show the features of this structure: the NW has morphological defects at both ends. The thickness of the NW varies sufficiently along the length, which is approximately 18 µm. A NW splitting (presence of additional NW) is observed in area 1, which is also confirmed by Raman integral intensity map (Fig. 2,*f*). The Raman spectrum obtained in area 1 has a characteristic shape for GaP NW (Fig. 2,*h*) and no any $MoSe_2$ vibration modes.

$MoSe_2$ layer thickness is found nonuniform demonstrated by the Raman integral intensity map in area 2 (Fig. 2,*g*). $MoSe_2$ layer thickness can be estimated not only by the Raman peaks position, but also by their presence. The presence and position of the A_{1g} and E^1_{2g} modes on the Raman spectrum (Fig. 2,*i*) correspond to a single-layer material [17]. There is a slight shift in the peak relating to the $MoSe_2$ bilayer [18] near the GaP NW tip, which indicates a fluctuation of the TMDC layer thickness. In the range of 750–825 nm (Fig. 2,*d*), the PL peak corresponding to the direct K-K transition in the monolayer is observed, and a long-wavelength shoulder corresponding to the K-K transition in the bilayer appears as a result of the thickness variation [19]. The peak in the shorter wavelength range (675–725 nm) appears due to spin-orbit splitting of the valence band at the K point of the $MoSe_2$ Brillouin zone [20].

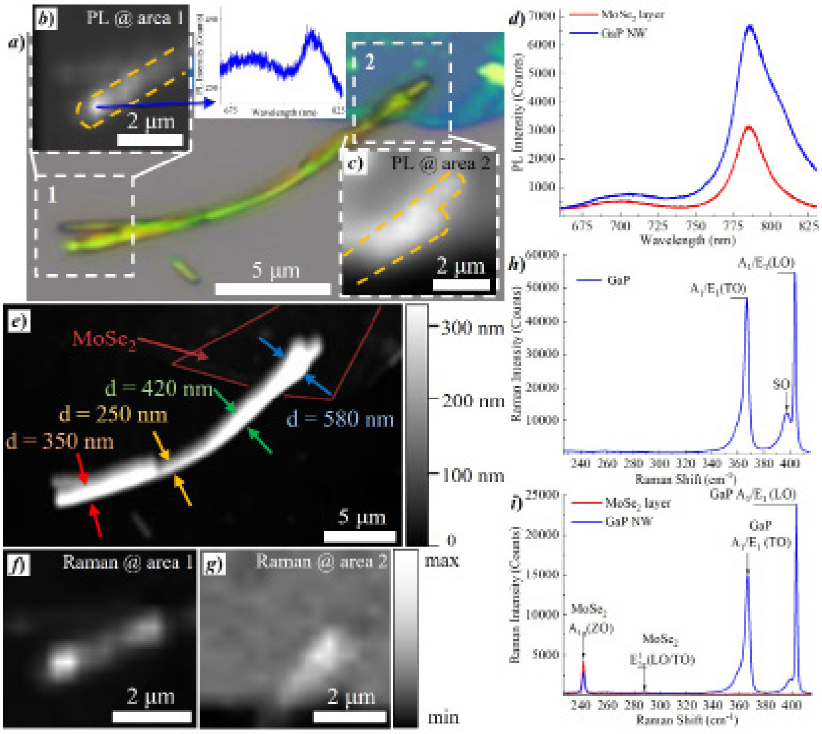

Fig. 2. Characterization of hybrid structures based on $MoSe_2$ and GaP NWs: Optical image of the hybrid structure (*a*); RT PL integral intensity maps of area 1 (*b*, with related PL spectrum of NW tip) and area 2 (*c*) in 650–830 nm range; PL spectra of the $MoSe_2$ layer and GaP NW in area 2 (*d*); AFM image of the of the hybrid structure (*e*); RT Raman integral intensity maps of areas 1 (*f*) and 2 (*g*) in 230–415 cm^{-1} range; Raman spectra of NW tip in area 1 (*h*) and $MoSe_2$ layer and GaP NW in area 2 (*i*)

The increase of the PL signal in the area 2 near the NW (Fig. 2, *c*, *d*) can be explained by light scattering on the structure defects. The shape of the PL spectrum obtained in the area 1 near the NW tip (spectrum relating to Fig. 2,*b*) corresponds to the PL spectrum shown in Fig. 2,*d*, which confirms the presence of the NW waveguiding and optical coupling with the $MoSe_2$ layer.

Conclusion

We demonstrate that both hybrid structures based on thin TMDC layers and GaP NWs exhibit anisotropic photoluminescence due to the combination of the TMDC layers radiative properties and the semiconductor NWs waveguiding. This result proves the possibility of directional transmission of optical signals at the nanoscale, which makes such structures promising for applications in integrated photonics.

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