Mid-infrared detectors for space electronics based on InAs-core/InP-shell nanowires

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Abstract

The Mid-Infrared (MIR) spectral range is most important for free-space communications and astronomy. It contains radiation emitted by astrophysical objects during evolution of the planets, stars, galaxies and in particular by prebiosignature molecules on exoplanets. Nanowires (NWs) are expected to improve various optoelectronic devices, including IR photodetector technology. The bandgap of the catalystless InAs NWs can be tuned by introducing mechanical strain due to lattice mismatches in the core/shell NWs structures. Passivation with wider bandgap InP shell provide highly tunable functionality for future electronic devices. Temperature dependence of photoluminescence (PL) spectra of NWs InAs and InAs-core/InP-shell was acquired using Fourier-spectrometer. The position of the high-energy PL peak between calculated values of Eg for wurtzite and sphalerite structures confirms the formation of NWs into a combined polytype. Low energy PL peak is connected with parasitic bulk islands. Surface passivation successfully eliminates surface states and provides nontrivial temperature dependence of high-energy PL peak due to tensile and compressive strain in InAs core. Thus, detectors based on NWs InAs and InAs-core/InP-shell structures can operate in the MIR range of the spectrum with a wavelength from 2 to 5 μm.

Keywords: *nanowires, passivation, detectors, radiation sources, photoluminescence*

1. Introduction

The infrared (IR) spectral range is one of the richest windows of the electromagnetic spectrum emitted by astrophysical objects during the evolution of planets, stars and galaxies. The Mid-IR (MIR) region is most important for free-space communications and astronomy, since the high transparency of the atmosphere at 3–5 μm and 8–12 μm allows transmission without significant atmospheric absorption (Tan & Mohseni (2018)). So it allows to trace star and planet formation, allows to study the first phases of galaxy evolution through stars and accreting black holes. Moreover, searching for biosignatures lying in MIR spectral range on exoplanets can reveal evidence of active biological processes on worlds beyond the Solar System. Studying molecules in exoplanet atmospheres associated with life (biosignatures) and its origins (prebiosignatures) such as, hydrogen cyanide (HCN), hydrogen sulfide (H_2S), cyanoacetylene (HCN), carbon monoxide (CO), methane (CH_4), acetylene (C_2H_2), ammonia (NH), nitric oxide (NO), and formaldehyde (CH_2O), can give us insight into the geochemical and physical processes occurring on terrestrial exoplanets (Claringbold et al. (2023)).

Semiconductor nanowires (NWs) have great prospects as a platform for electronic devices. NWs are expected to improve various optoelectronic devices (Zhang et al. (2015)). This is possible thanks to their significant advantages over thin films, quantum wells, and bulk materials due to their small size and small area of contact with the substrate. NWs can be easily synthesized on lattice-mismatched substrates such

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as Si, cheap glass, and even plastics (Khayrudinov et al. (2020)). Semiconductor NWs are highly flexible due to submicrometer diameters. Thus, this is possible to improve properties in particular IR photodetector technology which has various applications such as: infrared astronomy, free space optical communications, search and rescue, surveillance, missile tracking, night vision, navigation, weather monitoring, pollution measurement and so on.

The narrow bandgap of the InAs NWs attracts wide attention as a building base of future IR photodetectors and radiation sources. It can be tuned by introducing mechanical strain due to lattice mismatches in the core/shell NWs, providing highly tunable functionality for future devices (Rota et al. (2016)). Surface passivation with a wider-gap semiconductor improves optical properties by removing the influence of surface states, which have a significant effect due to the large surface-to-volume ratio of NWs (Treu et al. (2013)).

Detectors based on InAs NWs operate in the MIR spectral range with a wavelength of 2 to 5 μm, like Near-IR spectrograph on the James Webb Space Telescope, which covers 0.6–5.3 μm wavelength range (Jakobsen et al. (2022)).

2. Samples and experimental setup

Catalystless pristine InAs NWs and an InAs-core/InP-shell NWs with a coherent shell, were grown by molecular beam epitaxy on Si(111). Scanning electron microscopy (SEM) images of the samples reveal a bottom up structure of array InAs NWs with some amount of parasitic three-dimensional islands (see Fig. 1). The average diameter of one NW was about 200 μm. A high-resolution transmission electron microscopy (HRTEM) study of single NWs reveals that all synthesized NW heterostructures have a random hexagonal close-packed (RHCP) structure consisting of a random sequence of cubic and hexagonal stacking.

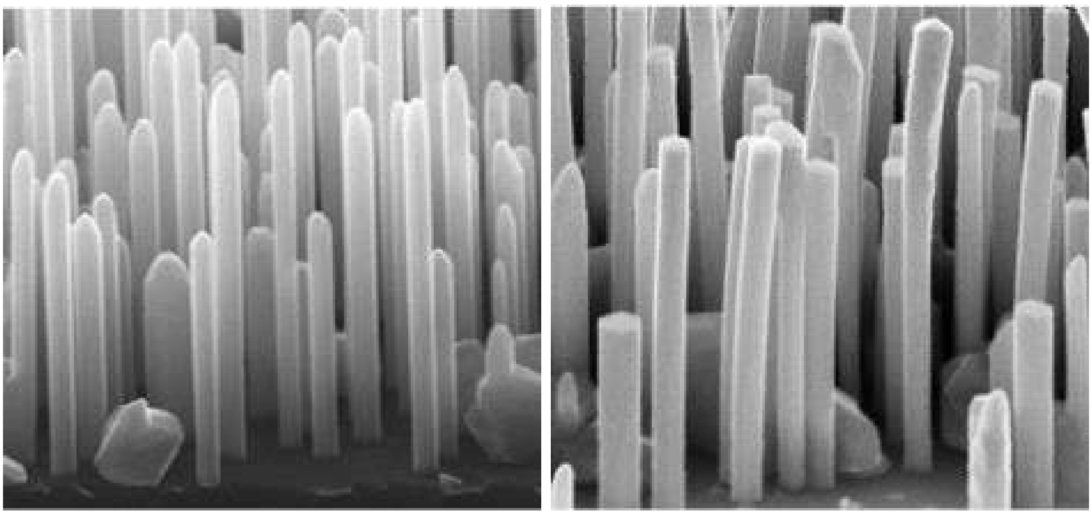

Figure 1. SEM images of pristine (on the left) and core/shell (on the right) InAs NWs.

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The energy-dispersive X-ray (EDX) map in the vicinity of NW tip shows that a significant volume of InP is formed at tapered NW tip, while the thickness of the InP shell grown on the NW side walls varies between opposite NW side facets and tends to decrease to the base of NW. Also TEM, XRD, and Raman results show the mechanical strain in the studied InAs-core/InP-shell NWs.

Photoluminescence spectra were obtained with a vacuum Fourier-spectrometer (Bruker Vertex 80v) working in the step-scan mode, with a KBr beam splitter and a Ge entrance window on the liquid nitrogen-cooled indium antimonide (InSb) photodetector. The sample was mounted into a closed-cycle cryostat (Janis PTCM-4-7) covered with a mid-IR light transparent ZnSe window. Optical pumping of the samples was provided by using a continuous wave diode pumped solid-state Nd/YAG laser (with photon energy about 1.16 eV) with an optical chopper (340 Hz). A photoluminescence signal from InSb photodetector was demodulated using a SR830 digital lock-in amplifier.

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3. Experimental results

During investigation, cryogenic PL spectra of pristine InAs NWs (see Fig. 2) and heterostructured InAs-core/InP-shell NWs (see Fig. 3) at different temperature and different optical pumping power were obtained. Two PL peaks are visible in all spectra. The low-energy peak corresponds to PL from parasitic islands of the bulk InAs sphalerite phase, and the high-energy peak corresponds to PL from NWs . Position of the high-energy PL peak is between the calculated values for Eg of wurtzite (481 meV) and sphalerite (411 meV), which confirms the formation of NWs into a combined polytype. No significant effect of optical pump power on the shape of the spectra was found.

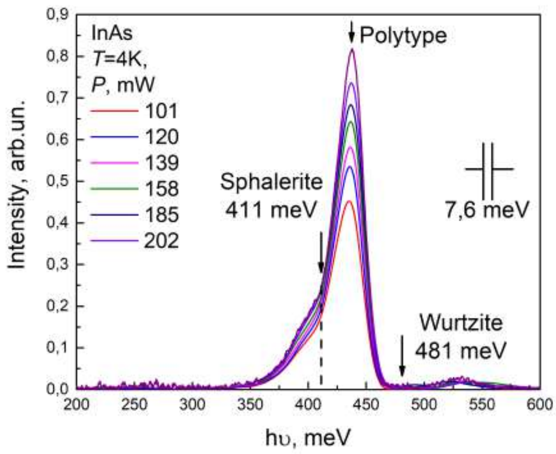

Figure 2. PL spectra of pristine NWs InAs at different levels optical pumping at 4 K.

With increasing temperature, the right PL peak of pristine InAs NWs behaves like Warshni low of Eg and moves to the low energy with the increase of temperature. Photoluminescence spectra of two different heterostructured InAs-core/InP-shell NWs with shell growth times of 10 minutes and 30 minutes demonstrate a nontrivial dependence on temperature of the position of the right PL peak. The PL signal level increases as the passivation layer increases, which indicates the successful elimination of surface states.

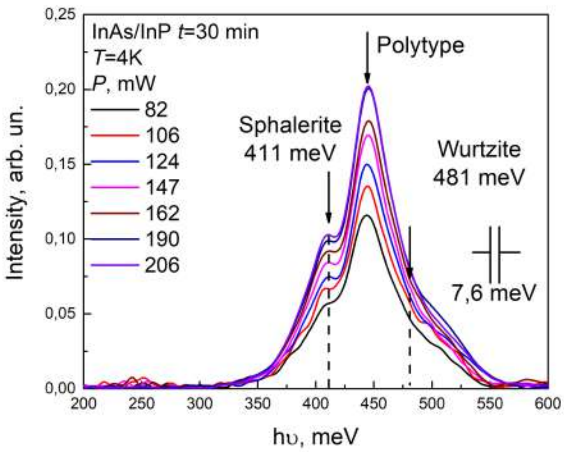

Figure 3. PL spectra of NWs InAs-core/InP-shell large shell at different levels optical pumping at 4 K.

On comparison of the PL spectra from three samples at same temperature and optical pumping, it can be seen that the PL spectra from passivated samples are shifted to higher energies, which indicates the presence of stresses exerted by the shell. The thicker the shell layer, the greater the compression and the greater the displacement.

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4. Conclusion

Thus, PL spectra of NWs pristine InAs and heterostructured InAs-core/InP-shell with different shell thickness were investigated. The bandgap of the InAs NWs can be adjusted by introducing mechanical strain due to lattice mismatche in the core/shell structure. Surface passivation with a wider-gap InP improves optical properties by removing the influence of surface states. So, it provides highly tunable functionality for future electronic devices in particular in IR photodetectors based on semiconductor InAs nanowires, wich can operate in the MIR range of the spectrum with a wavelength 2–5 μm, like Near-IR spectrograph on the James Webb Space Telescope, which covers 0.6–5.3 μm wavelength range.

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