RECENT ADVANCES IN ZnSe-BASED DEVICES: FROM UV TO TERAHERTZ APPLICATIONS

PROGRESE RECENTE ÎN ELABORAREA DISPOZITIVELOR PE BAZĂ DE ZnSe: APLICAȚII PENTRU DOMENIUL UV - THZ

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Zinc selenide is a II-VI compound material with wide bandgap. Due to its unique properties like direct wide bandgap, high resistance to intense UV and X-Ray radiation, ZnSe is attractive material for fabrication of many photonic and electronic devices. In this paper we report on recent advances on ZnSe-based optoelectronic devices covering spectral region from ultraviolet to terahertz.

Keywords: *terahertz radiation; quantum cascade lasers; photodetectors, ultraviolet radiation; zinc selenide.*

INTRODUCTION

Zinc selenide is a wide bandgap semiconductor which is attractive for fabrication of many optoelectronic devices, including the ultraviolet (UV) photodetectors, light-

emitting diodes and terhartez emitters due to its large bandgap energy (2.67 eV at 300 K), high electric field strength of breakdown (~ 1 MV/cm), as well as high resistance to intense UV and X-ray radiation [1-4]. Most commercial UV-photodetectors are based on Si or GaAs semiconductors, which require a filter to eliminate visible and infrared light. Moreover, the intense UV radiation induces aging effects in Si-based photodetectors that leads to its degradation. To solve this issue, the bulk high-resistivity ZnSe could be used for fabrication of a stable high-performance UV photodetectors with metal-semiconductor-metal (MSM) structure, as we shown recently [5]. The UV photodetectors based on MSM structures feature a very low capacitance in the fF-range, and thus could operate at high frequencies. Most ZnSe-based UV-photodetectors reported up to now are based on an epitaxial ZnSe active layer grown on a GaAs substrate by molecular beam epitaxy (MBE) or metal-organic chemical vapor deposition (MOCVD) techniques. At intense UV radiation, this thin epitaxial ZnSe layer could be damaged. In this case, a polycrystalline and block-structured ZnSe is a more suitable material for the fabrication of UV MSM photodetectors for intense UV radiation.

Also, zinc selenide could be attractive for fabrication of terahertz sources like resonant tunneling diodes (RTDs) and quantum cascade lasers (QCLs). Among the electron devices, resonant tunnelling diodes (RTDs) are promising as one of the candidates for terahertz wave generation and amplification, for signal detection and frequency mixing, all at room temperature. In the last decade significant progress has been made in the design and fabrication of THz RTDs based on AlGaAs/GaAs, InGaAs/AlAs, InGaAs/InAs and AlGaN/GaN material systems, but all these devices requires low temperature below the temperature of liquid nitrogen. To overcome this issue, II-VI compounds are considered as promising materials for high-power terahertz emitter devices due to the higher breakdown voltages and higher conduction band offset (CBO). For example, single crystals and polycrystalline ZnSe have a breakdown voltage up to 125 kV/cm in comparison with a value of 11 kV/cm for GaAs [6]. Moreover, among II-VI compounds, the ZnBeSe/ZnSe and ZnMgSe/ZnSe materials systems are attractive as promising materials for the fabrication of room-temperature THz RTD devices, due to the fact that this materials creates a type-I bandgap alignment.

In this paper we report on recent progress of development of ZnSe-based optoelectronic devices for spectral region from ultraviolet to terahertz.

METHODS AND EXPERIMENTAL TECHNIQUES

For fabrication ZnSe-based ultravioled photodetectors, high resistivity (~ 10^{12} **Ω** cm) bulk ZnSe crystals grown by the vapour phase method were used. The as-grown undoped ZnSe crystals were cut into pieces, polished mechanically and chemically in a 7% solution of Br-CH_3OH. After that, they were boiled in 40% NaOH and cleaned in acetone and in oxygen plasma. ZnSe-based UV photodetectors could have conventional and interdigital Ni/Au or Cr/Au contacts. Also devices where one of contacts is Ag-nanowire could be fabricated. Sirkeli et al. [3-5] reported on simulation study of room-temperature

Terahertz sources based on zinc selenide. For these simulations study the authors have used nextnano.MSB solver software. This software is based on modified non-equilibrium Green's function (NEGF) method employing the multi-scattering Büttiker probe (MSB) model for calculation of dissipative quantum transport in the multilayered quantum heterostructures. The following scattering mechanisms were taken into account in the MSB model: the electron-longitudinal optical (LO) phonon scattering, electron-electron scattering, electron-longitudinal acoustic (LA) phonon scattering. The LO-phonon energy of ZnSe is assumed to be 32 meV, and for MgSe to be 38 meV, and for $Zn_{1-x}Mg_xSe$ is linearly approximated between respective values of ZnSe and MgSe.

ZNSE-BASED ULRAVIOLET PHOTODETECTORS

The authors [6] reported on fabrication high performance ZnSe-based UV photodetectors with conventional and interdigital Cr/Au Schottky contacts. A maximum value of responsivity of 2.23 A W^{-1} at bias voltage of 15 V for light with a wavelength of 325 nm is found for this device. This value is few times higher than the maximum value of 0.13 A/W at 450 nm reported by Vigue et al. [1] for different types of ZnSe-based photodetectors. A maximum values of detectivity of ~ 9.86×10^{10} cm $Hz^{1/2}$ W^{-1} and photocurrent on/off ratio of 4219 at bias voltage of 15 V were obtained for this device. The measured response times of fabricated UV photodetectors is in the μs-range and is limited by the *RC* time of the measurement system. The UV photodetetctors with Cr/Ni conventional and interdigital contactacts could be attractive for high-speed UV telecommunications and UV-Tomography applications.

ZNSE-BASED TERAHERTZ DEVICES

The promising materials parameters of ZnSe have been exploited for a variety of Terahertz and photonic applications. The MgSe/ZnSe and BeSe/ZnSe material systems have a higher value of CBO of 0.9 eV and 1.5 eV, respectively, in comparison of value of 0.7 eV for AlAs/GaAs [3]. Furthermore, ZnSe crystals doped with transition metals (Mn, Ni, Cr, Fe, V and Co) are promising for fabrication of devices for spintronics, visible and infrared photonic applications [7-10]. In Ref. [3-5] authors we have numerically investigated the quantum transport in ZnBeSe/ZnSe resonant-tunneling diodes (RTDs) and ZnMgSe/ZnSe quantum cascade lasers (QCLs) with fixed and variable barrier heights at temperatures of 150 K and 300 K. The negative differential resistance (NDR) remains up to room temperature in the current-voltage characteristics of the RTD and QCL devices with variable barrier heights. It was established that the values of negative differential conductance (NDC) as compared with the PVR ratio have a strong influence on the frequency and output power performances of the investigated devices. QCLs with variable barrier heights have better frequency and power performance characteristics compared to RTDs and are more beneficial for high power terahertz generation at room temperature. For the best QCL device with 100 cascaded periods the maximum output power of ~ 7 ÷ 9 μW for the operating frequency range from 0.1 THz to ~ 15 THz at room

temperature was achieved. This value is of 4-5 orders of magnitude higher in the QCL structure with variable barrier heights in comparison with the value in the best ZnSe-based RTD devices.

CONCLUSIONS

Thus, recent papers on ZnSe shows significant progress in investigation of its optical and transport properties, as well as it perspective for fabrication high-performance ultraviolet photodetectors and QCL structures, that can be used as high-power terahertz oscillators at room temperature.

References:

1. F. VIGUE, E. TOURNIE, J.-P. FAURIE, “Evaluation of the potential of ZnSe and Zn(Mg)BeSe compounds for ultraviolet photodetection”, *IEEE Journal of Quantum Electronics* 2001, *37,* 1146. DOI: 10.1109/3.945319
2. SIRKELI, V.P., YILMAZOGLU, O., KÜPPERS, F., HARTNAGEL, H.L. *Effect of p-NiO and n-ZnSe interlayers on the efficiency of p-GaN/n-ZnO light-emitting diode structures*. În: Semicond. Sci. Technol. 2015, vol. 30, no. 6, 065005, doi: 10.1088/0268-1242/30/6/065005
3. SIRKELI, V.P., YILMAZOGLU, O., KÜPPERS, F., HARTNAGEL, H.L., “Room-temperature terahertz emission from ZnSe-based quantum cascade structures: A simulation study”, *Physica Status Solidi – Rapid Research Letters* **2017**, *11*, 1600423. DOI: 10.1002/pssr.201600423
4. SIRKELI, V.P., YILMAZOGLU, O., ONG, D.S., PREU, S., KÜPPERS, F., HARTNAGEL, H.L. *Resonant Tunneling and Quantum Cascading for Optimum Room-Temperature Generation of THz signals*. În: IEEE Transactions on Electron Devices. 2017, vol. 64, no. 8, pp. 3482-3488, doi: 10.1109/TED.2017.2718541
5. SIRKELI, V.P., YILMAZOGLU, O., PREU, S., KÜPPERS, F., HARTNAGEL, H.L. Proposal for a Monolithic Broadband Terahertz Quantum Cascade Laser Array Tailored to Detection of Explosive Materials. În: *Sens. Lett.* 2018, vol. 16, no. 1, pp 1-7, doi: 10.1166/sl.2018.3919
6. V. P. SIRKELI, O. YILMAZOGLU, A. S. HAJO, N. D. NEDEOGLO, D. D. NEDEOGLO, S. PREU, F. KÜPPERS, H. L. HARTNAGEL, “Enhanced Responsivity of ZnSe-Based Metal–Semiconductor–Metal Near-Ultraviolet Photodetector via Impact Ionization”, *Physica Status Solidi – Rapid Research Letters* 2018, 1*2*, 1600423. DOI: 10.1002/pssr.201700418
7. N. D. NEDEOGLO, V. P. SIRKELI, D. D. NEDEOGLO, R. LAIHO, E. LÄHDERANTA, “Electron configuration and charge state of electrically active Cu, Ag and Au ions in ZnSe”*, Journal of Physics: Condensed Matter* 2006, *18*, 8113. DOI: 10.1016/j.solidstatesciences.2015.10.018

8. V. SIRKELI, I. RADEVICI, K. SUSHKEVICH, H. HUHTINEN, N. NEDEOGLO. D. NEDEOGLO, P. PATURI, "MAGNETIC AND LUMINESCENT PROPERTIES OF NICKEL-DOPED ZNSE CRYSTALS"*, Solid State Sciences* 2015, *50*, pp. 74-80. DOI: 10.1016/j.solidstatesciences.2015.10.018
9. N. D. NEDEOGLO. D. D. NEDEOGLO, V. P. SIRKELI, I. M. TIGINYANU, R. LAIHO, E. LÄHDERANTA, "Shallow donor states induced in ZnSe:Au single crystals by lattice deformation"*, J. Appl. Phys.* 2008, *104*, 123717. DOI: 10.1063/1.3050327
10. I. RADEVICI, K. SUSHKEVICH, G. COLIBABA, V. SIRKELI, H. HUHTINEN, N. NEDEOGLO, D. NEDEOGLO, P. PATURI, "Influence of chromium interaction with native and impurity defects on optical and luminescence properties of ZnSe:Cr crystals", *J. Appl. Phys.* 2013, *114*, 203104. DOI: 10.1063/1.4837596

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