RECENT PROGRESS IN WIDE BANDGAP SEMICONDUCTORS-BASED DEVICES FOR TERAHERTZ APPLICATIONS

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Compact solid-state sources are important building blocks and key components of various terahertz applications. This spectral region, called also as “T-gap”, is important for many practical applications, including THz imaging, chemical and biological sensing, high-speed telecommunication, security and other applications. Moreover, THz spectral region covers intermolecular vibrations of biological molecules and low frequency crystalline lattice vibrations of chemical materials, including drugs, explosive and related compounds (ERCs) such as TNT, RDX, HMX, PETN and other explosive materials [1-3]. Among the electron devices, quantum cascade lasers (QCLs) and resonant tunneling diodes (RTDs) are promising as one of the candidates for terahertz wave generation and amplification at room temperature.

Despite the great progress in the last few years of design, fabrication and demonstration THz emitters based on GaAs/AlGaAs materials, there are some limits of bandgap engineering due to the relatively low (0.72 eV for GaAs/AlAs) conduction band offset (CBO). To overcome the issue the new material systems such as ZnMgO/ZnO, ZnBeSe/ZnSe and AlGaN/GaN are considered as promising for room-temperature THz sources [4-8]. III-Nitride materials, which include binary compounds InN, GaN, AlN and their alloys, have been investigated last several decades and are among the most important semiconductor materials for photonics, optoelectronics, high-power and high frequency electronics. These materials have a direct bandgap and their bandgap energy covers broad spectral range from the near infrared to deep ultraviolet: E_g = 0.7 eV for InN, E_g = 3.4 eV for GaN, and E_g = 6.2 eV for AlN [5, 6, 9, 10]. III-nitride materials can be doped n- and p-types using Si(Ge) or Mg impurities, respectively, and can be also grown heteroepitaxially on different foreign substrates, including sapphire, SiC and Si.

Bellotti et al. [6] theoretically established that the GaN/AlGaN-based THz QCLs could operate up to room temperature. The design of nitride-based THz QCL devices operating at room temperature is more complex than conventional GaAs/AlGaAs devices due to the spontaneous and piezoelectric polarizations in III-Nitride materials and the lattice mismatch.

Sirkeli et al. [7] reported on the design and simulation study of high power room-temperature THz QCLs based on a non-polar m-plane ZnMgO/ZnO material system with different design schemes, which include a 3-well design scheme with fixed barrier heights, a 2-well design scheme with fixed barrier heights, and a 2-well design scheme with variable barrier heights, respectively. These THz QCLs are based on designs with diagonal laser transitions, employing resonant-tunneling and intra-well depopulation of lower laser state mechanisms. As reference, the design of ZnMgO/ZnO THz QCL suggested by Bellotti et al. [6] was chosen. This THz QCL device consists of three ZnO quantum wells and $Zn_{0.85}Mg_{0.15}O$ quantum barriers. The approach for high-power room-temperature ZnMgO/ZnO THz QCLs suggested by Sirkeli et al. [7] is based on a 2-well design scheme employing the fixed and variable barrier heights and a delta-doped injector well of 1×10^{18} cm^{-3}. The THz QCL with fixed barriers consists of $Zn_{0.85}Mg_{0.15}O$ quantum barriers, while devices based on a design with variable barrier heights consist of $Zn_{0.80}Mg_{0.20}O$ and $Zn_{0.70}Mg_{0.30}O$ quantum barriers. For comparison, also the best experimental $Al_{0.15}Ga_{0.85}As$/GaAs THz QCL based on a 3-well design scheme [11] was simulated. The electronic quantum transport and optical gain of THz QCLs were investigated numerically within single-band effective mass approximation.

It is found that the optical gain of all devices decreased with increasing temperature. The calculated maximum operating temperature of AlGaAs/GaAs THz QCL is about 200 K, which is in good agreement with experiment [11]. The calculated radiation frequency of this device at 200 K is 3.50 THz, slightly higher than the experimental value of 3.22 THz. It is established, that among all devices, at room temperature the best value of optical gain of 300 cm^{-1} @ 4.96 THz is given by the ZnMgO/ZnO THz QCL with a 2-well

design scheme and variable barrier heights. This value is significantly higher than the performance of the other devices: 60 cm^{-1} @ 3.13 THz for ZnMgO/ZnO THz QCL with a 2-well design scheme and fixed barrier heights, and 1.4 @ 7.13 THz for ZnMgO/ZnO THz QCL with a 3-well design scheme and fixed barrier heights [7]. The higher laser performance of ZnMgO/ZnO THz QCLs compared with AlGaAs/GaAs is attributed to the higher LO-phonon energy in ZnO (72 meV for ZnO vs. 36 meV for GaAs).

In conclusion, we have provided a review of the recent progress and current status of wide bandgap semiconductors-based terahertz devices. It was established that ZnO, ZnSe and GaN-based compounds are promising materials for the fabrication of terahertz sources and detectors operating up to room temperature due to their unique properties such as large bandgap, CBO energy, and high LO-phonon energy. Moreover, the ZnO- and GaN-based terahertz sources can cover the spectral region of 0.1-12 THz, which is very important for THz imaging and detection of explosive materials, and which could not be covered by conventional GaAs-based terahertz devices.

References:

1. SIRKELI, V.P. et al. Resonant Tunneling and Quantum Cascading for Optimum Room-Temperature *Generation of THz signals*. In: *IEEE Transactions on Electron Devices,* 2017, vol. 64, no. 8, pp. 3482-3488, doi: 10.1109/TED.2017.2718541.
2. HARTNAGEL, H.L., SIRKELI, V.P. The use of metal oxide semiconductors for THz spectroscopy of biological applications. In: *IFMBE Proc.*, *Springer,* 2020, pp. 213–217, doi: 10.1007/978-3-030-31866-6_43.
3. SIRKELI, et al. 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.
4. SIRKELI, V.P., YILMAZOGLU, O., KÜPPERS, F., HARTNAGEL, H.L. Room-temperature terahertz emission from ZnSe-based quantum cascade structures: A simulation study. In: *Phys. Status Solidi - Rapid Res. Lett,* 2017, no. 11, no. 3, 1600423, doi: 10.1002/pssr.201600423.
5. SIRKELI, V. Recent progress in GaN-based terahertz sources: a review. În: *Revista de ştiinţă, inovare, cultură şi artă „Akademos”*, 2018, vol. 50, nr. 3, pp. 24-32. ISSN 1857-0461.

6. BELLOTTI, E., DRISCOLL, K., MOUSTAKAS, T.D., PAIELLA, R. Monte Carlo simulation of terahertz quantum cascade laser structures based on wide-bandgap semiconductors. In: *J. Appl. Phys*, 2009, vol. 105, no. 11, 113103, doi: 10.1063/1.3137203.
7. SIRKELI, V.P., HARTNAGEL, H.L. ZnO-based terahertz quantum cascade lasers. In: *Opto-Electronics Review*, 2019, vol. 27, no. 2, pp. 119-122. ISSN 1230-3402, doi: 10.1016/j.opelre.2019.04.002.
8. SIRKELI, V. Quantum Nanostructures for Terahertz Devices and Applications. In: *NANO-2019*: *Limits of Nanoscience and Nanotechnologies*, 24-27 septembrie 2019, Chișinău, Republica Moldova. 2019, p. 26.
9. SIRKELI, V.P. et al. Efficiency enhancement of InGaN/GaN light-emitting diodes with pin-doped GaN quantum barrier. In: *Journal of Physics D: Applied Physics*, 2017, vol. 50, no. 3, 035108, doi: 10.1088/1361-6463/50/3/035108
10. 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. In: *Semicond. Sci. Technol*, 2015, vol. 30, no. 6, 065005, doi: 10.1088/0268-1242/30/6/065005.
11. FATHOLOLOUMI, S. et al. *Terahertz quantum cascade lasers operating up to ∼ 200 K with optimized oscillator strength and improved injection tunneling*. In: *Opt. Express*, 2012, vol. 20, no. 4, pp. 3866, doi: 10.1364/oe.20.003866.

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