Semiconductor Physics, Quantum Electronics & Optoelectronics, 2024. V. 27, No 4. P. 384-388.

Editorial

Development of terahertz approaches for optoelectronics and the SPQEO journal

Z. Tsybrii, O. Golenkov, Z. Maksimenko & P. Smertenko

V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine
41 Nauky Avenue, 03028 Kyiv, Ukraine
Corresponding author e-mail: petrosmertenko@gmail.com

Abstract. This article discusses the main trends in the development of terahertz (THz) optoelectronics, which bridge the gap between traditional electronics and the unexplored part of electromagnetic spectrum known as the "THz gap". Each of the THz bands: the submillimeter range (0.1 to 0.3 THz), the low range (0.3 to 1 THz), the midrange (1 to 3 THz), the high range (3 to 10 THz), and the ultrafast range (above 10 THz) requires development of specific research approaches, materials, devices and applications. This article reports on the contribution of SPQEO journal to the development of THz optoelectronics over the past decade, in particular, (i) spintronics phenomena induced by THz radiation in narrow-gap HgCdTe thin films under an external DC electric field; (ii) the possibility of realizing two-color uncooled narrow-gap mercury-cadmium-telluride semiconductor as a direct detection bolometer in the sub-THz range and an IR photoconductor in the 3–10 µm range with the parameters suitable for many applications; (iii) design and fabrication of aspherical polystyrene lenses for the THz range; (iv) the possibility of using the convolutional neural network method for image recognition from THz scanners, *etc*.

Keywords: SPQEO journal, THz optoelectronics, THz time-resolved spectroscopy, image recognition, narrow-gap HgCdTe thin film.

https://doi.org/10.15407/spqeo27.04.384
PACS 68, 73, 77, 78, 81, 85.30.-z, 85.35.B2

Manuscript received 29.10.24; revised version received 14.11.24; accepted for publication 13.11.24; published online 06.12.24.

1. Modern state of terahertz science and technology

In recent decades, terahertz investigations have stormed into research groups and allowed humanity to look into a different part of the electromagnetic spectrum invisible to a human eye and quite far from traditional electronics, which was called the "THz gap" [1, 2]. Analysis of the publication trends in the field of THz optoelectronics over the past 10 years shows a steady increase in research output, reflecting its growing importance and the expanding scope of applications [3, 4]. In fact, it would be impossible to even mention all the disciplines related to terahertz optoelectronics. Therefore, in Fig. 1, we have tried to chart the scientific and technological areas of terahertz Optoelectronics and to cover very briefly its main modern trends. Traditionally, terahertz optoelectronics is divided into five bands. For all of them, the key topical THz developments include both fundamental scientific research (terahertz quantum optics, spintronics and magnetism, astronomy *et al.*) and commercial and social impactful subjects (THz imaging, medical application, THz communication, climate monitoring and forecasting). For example, development of terahertz *time-domain spectroscopy* (THz-TDS) is one of the most significant achievements in terahertz technology, which has revolutionized this field by enabling precise measurements of materials properties, such as refractive index and absorption coefficients [5]. The new field of the THz-TDS, namely the time-domain quantum optics, brings the established technology of generation and characterization of classical THz electric fields to quantum regime. It can provide a resource to resolve fundamental questions in quantum physics, extending even to cosmological context. In particular, characterization of photon-antiphoton clouds at elementary timescales, observation of vacuum entanglement, direct detection of Unruh radiation and control of its properties may be envisioned. From the practical viewpoint, it might lead to time-domain tomography of quantum fields and further on to quantum spectroscopy [4].

The second very important topic is *imaging*, where terahertz waves have demonstrated their potential for non-destructive testing and evaluation. Recent advances in real-time multipixel THz imaging systems have made it possible to obtain high-resolution three-dimensional images of various materials and biological tissues. For

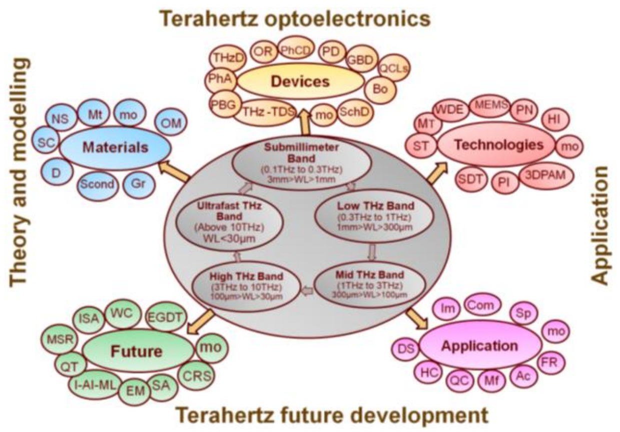


Fig. 1. Conventional division of terahertz areas. Here, the following abbreviations are used. WL is wave length; mo is many others; *Materials:* Scond is semiconductors (GaAs, InP, CdHgTe), Gr is graphene, Mt is metamaterials, D is dielectrics, SC is superconductors, NS is nanostructures, OM is organic materials;
Devices: PhA is photoconductive antennas, QCLs is quantum cascade lasers, THz-TDS is THz time-domain spectroscopy, OR is optical rectification, PBG is plasma-based generators, THzD is THz detectors, Bo is bolometers, PhCD is photoconductive detectors, SchD is Schottky Diodes, PD is pyroelectric detectors, GBD is graphene-based detectors;
Technologies: ST is semiconductor technologies, MT is microfabrication techniques, WDE is wet and dry etching, PN is plasmonic nanostructuring, 3D-PAM is 3D printing and additive manufacturing, MEMS is MEMS technologies, HI is hybrid integration, SDT is slicing and dicing techniques, PI is packaging and integration;
Application: Im is imaging, Com is communication, Sp is spectroscopy, HC is healthcare, QC is quantum computing, Mf is manufacturing, FR is fundamental research, DS is defense and security, Ac is agriculture.
Future: EGDT is enhanced generation and detection techniques, WC is wireless communication, ISA is imaging and sensing applications, MSR is material science and research, QT is quantum technologies, EM is environmental monitoring, I-AI-ML is integration with AI and Machine Learning, CRS is cost reduction and scalability, SA is security and authentication.

example, terahertz imaging has been used to detect explosives, drugs, defects in composite materials, to monitor hydration levels in plants, and even diagnose diseases such as diabetic foot ulcers [6].

The study of *nonlinear optical effects* in the terahertz range has opened up new avenues for research. Nonlinear terahertz spectroscopy allows scientists to study ultrafast dynamics in materials, providing insight into phenomena such as carrier transport and molecular vibrations. It is predicted that intense terahertz fields can cause nonlinear phenomena in some new materials, as has already been demonstrated in graphene. These studies are crucial to deepening our understanding of fundamental physical processes and developing new terahertz devices [7].

Importantly, the *integration* of terahertz technology *with silicon photonics* has helped accelerate its development due to its compactness, scalability, and compatibility with existing semiconductor manufacturing processes. This integration has paved the way for the development of terahertz communication systems that promise to provide ultrafast wireless data transmission, potentially exceeding the speeds of current 5G networks. Most of the developed THz wireless communication systems operate below 300 GHz. In order to reach a data rate greater than 1 Tbps (6G networks), it is almost certain that the operating frequency will be above 300 to about 500 GHz. According to the International Techno-logy Roadmap for Semiconductors, the cut-off frequency of the silicon complementary metal-oxide-semiconductor (Si-CMOS) technology will exceed 500 GHz within a few years [8].

Despite significant achievements, challenges for widespread adoption of terahertz technology remain: material limitations (many traditional semiconductor materials are not well-suited for THz frequencies); sensitivity to environmental conditions (THz waves are highly sensitive to humidity and temperature, which may affect performance and reliability); device efficiency (current sources and detectors often suffer from low output power and sensitivity); high cost; low compactness; a lack of standardization in THz technology.

2. THz semiconductor detectors, modelling of antenna patterns and design of optical components

Our previous consideration of optoelectronics trends [9] rated terahertz optoelectronics to be a very important and perspective area both for future development of optoelectronics and for SPQEO journal. Over the past 10 years, the SPQEO journal has regularly published topical theoretical and experimental research works devoted to the development of THz technologies and their application. A part of the published articles was dedicated to the development of THz semiconductor detectors, modelling of antenna patterns and design of optical components [10–16]. Thus, the possibility of realizing two-color uncooled narrow-gap mercury-cadmium-telluride semiconductor as sub-terahertz direct detection bolometers and 3–10 μm IR photoconductor with the parameters suitable for many applications was presented in [13]. For HgCdTe detectors from an array used for sensing sub-THz radiation at ν = 140 GHz, the measured noise was about 30 $nV \cdot Hz^{-1/2}$ at 3-mA bias and the corresponding noise equivalent power value was $NEP_{300K} \approx (4.5…9) \cdot 10^{-10}$ $W/Hz^{1/2}$ that may be supposed as sufficient for active imaging.

Investigations of spintronics phenomena induced by THz radiation in narrow-gap HgCdTe thin films in an external constant electric field were presented in [17, 18]. The papers report detection of strong polarization-dependent THz photo-responses in $Hg_{1-x}Cd_xTe$ ($x \approx 0.201$) photoconductors with normal band ordering having large spin-orbit coupling and irradiated by normal to the photoconductor surface THz radiation (linearly or circularly polarized). The observed effects were assumed to be due to the Rashba spin splitting in HgCdTe, caused by large spin-orbit interactions. Presumably, the oscillating photoresponses under polarized THz radiation in these unbiased and biased structures are related to the circular and linear photogalvanic effects without and with an external electric field. The observed features of the polarized dependent photoresponse may be important for spintronics applications at elevated temperatures.

For collecting, focusing or collimating THz radiation and then inputting it into detectors and getting imaging, one needs to use an optical system consisting of lenses or mirrors. Designing and manufacturing aspherical polystyrene lenses for the THz region is presented in [11]. Aspherical lenses, compared to conventional spherical lenses, allow correction of aberrations with fewer optical lenses, hence, an optical system can have lower price and be more compact in size. It was proposed to use cylindrical lenses for applications requiring one-dimensional shaping of a light source such as a line of detectors. THz lenses made of high impact polystyrene material (HIPS) by 3D printing were designed, manufactured and successfully tested with a 32 elements linear detector array at 140 GHz radiation.

One more interesting topic concerning the possibility of the convolutional neural network (CNN) methodology for image recognition from the THz scanner developed by the authors was published in [19]. The active terahertz vision direct detection system has been developed using continuous IMPATT diode radiation sources with the operation frequency of 140 GHz (λ = 2.14 mm) and detector Si-MOSFET linear arrays with matched parameters of arrays and optical unit providing spatial resolution $\Delta \approx 5$ mm. The possibility of application-ready pre-trained models from the Tensorflow Object Detection library to snapshots from the developed 0.14 THz scanner was demonstrated. With the signal-to-noise ratio from 35 to 48 dB provided by the scanner, the trained models were sustainable and not influenced by artefacts from the scanner snapshots. The trained RCNN Inception model showed promising results in binary experiments with the accuracy close to 97 percent.

The article [20] reported about fabrication of the following equipment: (i) detector sections for the 220–325 GHz and 325–400 GHz frequency ranges that ensure conversion factor within 1000–115 V/W and 120–102 V/W, respectively; (ii) radiation source using master-oscillator with a silicon IMPATT diode (operating frequency of 140 GHz) and frequency doubler with SBD (operating frequency of 280 GHz and output power of 0.3–0.5 mW); and (iii) subharmonic mixers for the 220–325 GHz and 325–400 GHz frequency ranges, with conversion losses no more than 30 dB. This equipment was developed using mathematical modeling of detector sections, radiation source and subharmonic mixers.

3. Theoretical studies in sub-THz and THz frequency range

The main features of the amplitude and phase transmission/reflection spectra of various model semiconductor structures were discussed in [21]. Bare dielectric substrates, a thin conductive layer placed between two dielectric media, a thin conductive layer on a dielectric substrate, and hybrid plasmonic structures with a thin conductive layer under a metal lattice were considered. The analysis was performed using the analytical expressions obtained by solving the Maxwell equations at normal incidence of plane electromagnetic waves. The basic electrical parameters of an electronic gas were determined by the specific behavior of the amplitude and phase spectra in the THz frequency range. These parameters included electron concentration and electron mobility in the framework of advanced terahertz time-domain measurements. In this study, an efficient electrically-controllable THz phase modulator was proposed. It was based on a two-dimensional plasmon resonance effect in a hybrid plasmonic structure with a spatially modulated electron concentration in conductive thin layers.

The optical properties of grating-based AlGaN/GaN plasmonic structures with low-doped 2D electron gases were measured using terahertz time-domain spectroscopy and modeled by rigorous electrodynamic modeling [22]. The samples with grating aspect ratios (strip width/period) of 2.4/3 and 1.2/1.5 μm were studied. It was shown that specific values of amplitude and spectral position of the transmission maxima are related to the coupling of the plasmon excitation induced THz radiation to the 2D electron gas. Calculations and measurements of transmission/reflection have demonstrated a threefold increase in the non-resonant absorption of THz radiation in plasmonic structures with micro-scaled metallic grating compared to bare hetero-structures. Values of the transmission coefficient obtained for *p*-polarized and *s*-polarized incident radiation demonstrated the high quality of the deposited metal gratings with extinction ratios higher than 80:1 in the sub-THz and several THz frequency range.

4. Conclusion

The growing research in terahertz optoelectronics highlights its enormous potential for a wide range of applications, from basic scientific research to commercial technologies with broad societal impact. Key advances such as terahertz time-domain spectroscopy and high-resolution imaging have transformed the field, enabling applications in materials science, healthcare and security.

SPQEO journal revenues in the field of terahertz optoelectronics include: (i) spintronic phenomena induced by terahertz radiation in narrow-gap HgCdTe thin films under an external DC field; (ii) realization of the potential of two-color, uncooled, narrow-gap HgCdTe semiconductors as a wavelengthmeter for direct detection in the subterahertz range, with parameters suitable for a wide range of applications for 3–10 μm infrared optoelectronics; (iii) design and fabrication of terahertz optoelectronic devices; (iv) design and fabrication of a new, more advanced terahertz technology; (v) design and fabrication of aspheric polystyrene lenses for the terahertz range; (vi) possibility of image recognition from terahertz scanners using the convolutional neural network method, *etc*.

References

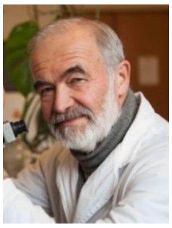
1. Sizov F.F. Infrared and terahertz in biomedicine. *SPQEO*. 2017. **20**. P. 273–283. https://doi.org/10.15407/spqeo20.03.273.
2. Sizov F.F. Brief history of THz and IR technologies. *SPQEO*. 2019. **22**. P. 67–79. https://doi.org/10.15407/spqeo22.01.67.
3. Irizawa A., Lupi S., Marcelli A. *et al.* Terahertz as a frontier area for science and technology. *Condens. Matter*. 2021. **6**, No 3. P. 23. https://doi.org/10.3390/condmat6030023.
4. Leitenstorfer A., Moskalenko A.S., Kampfrath T. *et al*. The 2023 terahertz science and technology roadmap. *J. Phys. D: Appl. Phys*. 2023. **56**, No 22. P. 223001. https://doi.org/10.1088/1361-6463/acbe4c.
5. Mittleman D.M. Perspective: Terahertz science and technology. *J. Appl. Phys.* 2017. **122**. P. 230901. https://doi.org/10.1063/1.5007683.
6. Castro-Camus E., Koch M., Mittleman D.M. Recent advances in terahertz imaging: 1999 to 2021. *Appl. Phys. B*. 2022. **128**. P.12. https://doi.org/10.1007/s00340-021-07732-4.
7. Xie J., Ye W., Zhou L. *et al.* A review on terahertz technologies accelerated by silicon photonics. *Nanomaterials*. 2021. **11**, No 7. P. 1646. https://doi.org/10.3390/nano11071646.
8. Huang Y., Shen Y., Wang J. From terahertz imaging to terahertz wireless communications. *Engineering*. 2023. **22**. P. 106–124. https://doi.org/10.1016/j.eng.2022.06.023.
9. Smertenko P., Pekur D., Sorokin V., Maksimenko Z. Optoelectronics and the SPQEO journal. *SPQEO*. 2024. **27**. P. 256–260. https://doi.org/10.15407/spqeo27.03.256.
10. Shevchik-Shekera A.V. Sizov F.F., Golenkov O.G. *et al.* Silicon lenses with HDPE anti-reflection coatings for low THz frequency range. *SPQEO*. 2023. **26**. P. 059–067. https://doi.org/10.15407/spqeo26.01.059.
11. Shevchik-Shekera A., Zabudsky V., Golenkov A., Dvoretsky S. Designing and manufacturing polystyrene lenses for the terahertz region. *SPQEO*. 2018. **21**. P. 83–88. https://doi.org/10.15407/spqeo21.01.083.
12. Kukhtaruk N.I., Zabudsky V.V., Shevchik-Shekera A.V. *et al.* In–HgCdTe–In structures with symmetric nonlinear *I–V* characteristics for sub-THz direct detection. *SPQEO*. 2017. **20**. P. 173–178. https://doi.org/10.15407/spqeo20.02.173.
13. Golenkov A.G., Sizov F.F. Performance limits of terahertz zero biased rectifying detectors for direct detection. *SPQEO*. 2016. **19**. P. 129–138. https://doi.org/10.15407/spqeo19.02.129.
14. Sizov F.F., Tsybrii Z.F., Zabudsky V.V. *et al.* Detection of IR and sub/THz radiation using MCT thin layer structures: design of the chip, optical elements and antenna pattern. *SPQEO*. 2016. **19**. P. 149–155. https://doi.org/10.15407/spqeo19.02.149.
15. Golenkov A.G., Zhuravlev K.S., Gumenjuk-Sichevska J.V. *et al.* Sub-THz nonresonant detection in AlGaN/GaN heterojunction FETs. *SPQEO*. 2015. **18**. P. 040–045. https://doi.org/10.15407/spqeo18.01.040.
16. Shevchik-Shekera A.V., Dukhnin S.E. Design of optical components for terahertz/sub-terahertz imaging systems. *SPQEO*. 2015. **18**. P. 341–343. https://doi.org/10.15407/spqeo18.03.341.
17. Sizov F.F., Gumenjuk-Sichevska J.V., Danilov S.N., Tsybrii Z.F. Spin-dependent polarization response in HgCdTe hot-electron bolometers. *SPQEO*. 2022. **25**. P. 254–261. https://doi.org/10.15407/spqeo25.03.254.
18. Tsybrii Z.F. Danilov S.N., Gumenjuk-Sichevska J.V. *et al.* Spintronics phenomena induced by THz radiation in narrow-gap HgCdTe thin films in an external constant electric field. *SPQEO*. 2021. **24**. P. 185–191. https://doi.org/10.15407/spqeo24.02.185.
19. Golenkov A.G., Gumenjuk-Sichevska J.V., Kovbasa M.Yu. *et al.* THz linear array scanner in application to the real-time imaging and convolutional neural network recognition. *SPQEO*. 2021. **24**. P. 90–99. https://doi.org/10.15407/spqeo24.01.090.
20. Zorenko O.V., Bychok A.V., Kryts'ka T.V. *et al*. Hybrid-integrated version of solid-state components for terahertz frequency region. *SPQEO*. 2014. **17**. P. 193–199. https://doi.org/10.15407/spqeo17.02.193.
21. Lyaschuk Yu.M., Korotyeyev V.V., Kochelap V.A. Peculiarities of amplitude and phase spectra of semiconductor structures in THz frequency range. *SPQEO*. 2022. **25**. P. 121–136. https://doi.org/10.15407/spqeo25.02.121.
22. Korotyeyev V.V., Lyaschuk Yu.M., Kochelap V.A. *et al.* Interaction of sub-terahertz radiation with low-doped grating-based AlGaN/GaN plasmonic structures. Time-domain spectroscopy measurements and electrodynamic modeling. *SPQEO*. 2019. **22**. P. 237–251. https://doi.org/10.15407/spqeo22.02.237.

Authors and CV

Zinoviia F. Tsybrii, Doctor of Sciences, Head of Department at the V. Lashkaryov Institute of Semiconductor Physics. The area of her scientific interests includes physics and technology of semiconductor materials, heterostructures and devices (IR and THz detectors, nanomaterials, *etc*.). E-mail: tsybrii@isp.kiev.ua, http://orcid.org/0000-0003-1718-5569.

Oleksandr G. Golenkov, PhD, Senior Researcher at the V. Lashkaryov Institute of Semiconductor Physics. Authored over 100 publications and 8 patents. The area of his scientific interests includes nonlinear optics, infrared and terahertz detectors based on HgCdTe, InSb and Si-FETs, matrix and linear array detectors, and developing IR and THz testing and vision systems.
E-mail: golenkov@isp.kiev.ua,
https://orcid.org/0000-0001-8009-7161

Zoia Maksimenko, PhD in Physics and Mathematics, Researcher at the Department of Ion-beam Engineering and Structural Analysis, V. Lashkaryov Institute of Semiconductor Physics. The main direction of her scientific activity is studying semiconductor nanostructures by high-resolution X-ray diffractometry in the field of anomalous X-ray dispersion.
E-mail: ZMaksimenko@gmail.com,
https://orcid.org/0000-0002-3434-3728



Petro Smertenko, Senior Researcher at the Department of Kinetic Phenomena and Polaritonics of the V. Lashkaryov Institute of Semiconductor Physics, PhD in Physics and Mathematics. Authored over 150 publications, 30 patents, and 8 textbooks. The area of his scientific interests includes physics and technology of semiconductor materials, hetero- and hybrid structures and devices (solar cells, photoresistors, light-emitting structures, *etc.*) as well as analysis, diagnostics, modeling and forecast of electrophysical processes in various objects.
http://orcid.org/0000-0001-8793-302X

Authors' contributions

Tsybrii Z.: resources, methodology, writing – original draft, writing – review & editing.
Golenkov O.: data curation (partially), resources.
Maksimenko Z.: visualization, data curation (partially), writing – review & editing.
Smertenko P.: verification, formal analysis, investigation, data curation (partially), writing – original draft, writing – review & editing.

Розвиток терагерцових підходів до оптоелектроніки та журнал SPQEO

З.Ф. Цибрій, О.Г. Голенков, З.В. Максименко та П.С. Смертенко

Анотація. У цій статті розглядаються основні тенденції розвитку терагерцової (ТГц) оптоелектроніки, яка долає розрив між традиційною електронікою і недослідженою частиною електромагнітного спектра, відомою як «ТГц розрив». Кожна з областей ТГц: субміліметровий діапазон (від 0,1 до 0,3 ТГц), низький діапазон (від 0,3 до 1 ТГц), середній діапазон (від 1 до 3 ТГц), високий діапазон (від 3 до 10 ТГц) і надшвидкісний діапазон (понад 10 ТГц) вимагає розробки спеціальних дослідницьких підходів, матеріалів, пристроїв і застосувань. У цій статті розповідається про внесок SPQEO у розвиток надвисокочастотної оптоелектроніки за останнє десятиліття: зокрема, (i) явища спінтроніки, індуковані ТГц випромінюванням у вузькощілинних тонких плівках HgCdTe під зовнішнім постійним електричним полем; (ii) можливість реалізації двоколірного неохолоджуваного вузькощілинного напівпровідника ртуть-кадмій-телур як болометра прямого детектування в субтерагерцовому діапазоні та ІЧ фотопровідника для спектральної області 3–10 мкм з параметрами, придатними для багатьох застосувань; (iii) проектування та виготовлення асферичних полістирольних лінз для ТГц діапазону; (iv) можливість використання методу згорткових нейронних мереж для розпізнавання зображень з ТГц сканерів тощо.

Ключові слова: журнал SPQEO, ТГц оптоелектроніка, ТГц спектроскопія з часовою роздільною здатністю, розпізнавання зображень, вузькощілинна тонка плівка HgCdTe.