
V. Ryzhii

T. Otsuji, M. Ryzhii, V. Leiman, V. Mitin, M. S. Shur

RIEC, Tohoku University, Sendai 980-8577, Japan; Dept. CSE, University of Aizu, Aizu-Wakamatsu, Japan; CP2DM, Moscow Institute of Physics and Technology, Dolgoprudny, Russia; Dept. EE, University at Buffalo, Buffalo, USA; Dept. ECSE, Rensselaer Polytechnic Institute, Troy, USA

v-ryzhii@riec.tohoku.ac.jp

Concepts of Terahertz and Infrared Devices based on Graphene/Black Phosphorus-Arsenic Heterostructures

The gapless energy spectrum of the graphene layers (GLs) [1] enables the interband absorption and emission of photons and plasmons in the terahertz (THz) and infrared (IR) spectral range. The energy gap, Δ_G , of the emerging the black-phosphorus (b-P), black-Arsenic (b-As), and the compounds $b\text{-P}_{1-x}\text{As}_x$ varies from 0.15 to 1.2 eV, depending on the number of the atomic sheets and the component relative content. Due to a strong anisotropy of the b-P and b-As, the ratios of the electron effective masses (as well as the hole effective masses) in different in-plain directions are very large. One of the crucial properties of the GL heterostructures with the b-P, b-As, and A_xP_{1-x} barrier layers are associated with the GL Dirac point corresponding to the energy gap in the barriers. Combining GLs with the b-P, b-As, and $b\text{-As}_x\text{P}_{1-x}$ layers opens new prospects for the novel THz and IR devices [2–10], in particular, GL-based photodetectors (GLIPs), electro-optical modulators and sources of THz/IR radiation.

In this presentation, we review the concepts of THz and IR photodetectors, sources, switches, and modulators based on the heterostructures in question focusing on our recent results (see [11- 18]).

The following devices are considered:

- THz and IR photodetectors based on the vertical G/b- $P_{1-x}\text{As}_x$ heterostructures and using the interband transitions in the GLs followed by the carrier propagation across the $b\text{-P}_{1-x}\text{As}_x$ layers and the injection of the extra carriers from the emitter contact. The latter provides the photoconductive gain and fairly high values of the detector responsivity [11-14];
- Sources of the THz radiation using the vertical injection from the $b\text{-A}_x\text{P}_{1-x}$ emitter layer. A relatively small energy gap in such layers and an appropriate band alignment enable the injection of carriers with moderate energies from the emitter into the GL. This helps the realization of the interband population inversion [15,16];
- Devices based on the lateral GL/b- A_xP_{1-x} heterostructures using the real space transfer of the light carriers from the GL to the neighboring $b\text{-A}_x\text{P}_{1-x}$ layers, in which the carriers are rather heavy. These devices can be used as logical switches and electro-optical modulators of the THz radiation by controlling the effective carrier temperature by the electric field. They could be used as bolometric THz detectors utilizing heating of the carriers by the incident THz radiation combined with their real-space transfer [17, 18].

References

- [1] K.S. Novoselov, and A. K. Geim, Rev. Mod. Phys. **81**, 109 (2009).
- [2] R. W. Keyes, Phys. Rev. **92**, 580 (1953).
- [3] A. Morita, Appl. Phys. A **39**, 227 (1986).
- [4] H. Asahina and A. Morita J. Phys. C: Solid State Phys. **17**, 1839 (1984).
- [5] Xi Ling, H. Wang, S. Huang, F. Xia, and M. S. Dresselhaus, PNAS **112**, 4523 (2015).

- [6] F. Xia, H. Wang, Y. Jia, Nat. Comm. **5**, 4458 (2014).
- [7] Z. Guo, H. Zhang, S. Lu, Z. Wang, S. Tang, J. Shao, Z. Sun, H. Xie, H. Wang, X.-F. Yu, and P. K. Chu, Adv. Funct. Mat. **25**, 6996 (2015).
- [8] B. Liu, M. Kopf, A. N. Abbas, X. Wang, Q. Guo, Y. Jia, F. Xia, R. Weihrich, F. Bachhuber, F. Pielhofer, H. Wang, R. Dhall, S. B. Cronin, M. Ge, X. Fang, T. Nilges, and C. Zhou, Adv. Mater. **27**, 4423 (2015).
- [9] M. Long, A. Gao, P. Wang, et al. Sci. Adv. **3**, No.6, e1700589 (2017)
- [10] S. Yuan, C. Shen, B. Deng, et al, Nano Lett. **18**, 31723179 (2018).
- [11] V. Ryzhii, M. Ryzhii, D. Svintsov, V. Leiman, V. Mitin, M. S. S Shur, and T. Otsuji, Infrared Phys. Technol. **84**, 72 (2017),
- [12]. V. Ryzhii, M. Ryzhii, V. Leiman, V. Mitin, M. S. Shur, and T. Otsuji, J. Appl. Phys. **122**, 054505 (2017).
- [13] V. Ryzhii, M. Ryzhii, D. Svintsov, V. Leiman, V. Mitin, M. S. S Shur, and T. Otsuji, Opt. Exp. **25**, 5536 (2017).
- [14] V. Ryzhii, T. Otsuji, V. E. Karasik, M. Ryzhii, V. G. Leiman, V. Mitin, and M. S. Shur, IEEE J. Quantum Electron. **54**, No.2 (2018).
- [15] V. Ryzhii, T. Otsuji, M. Ryzhii, A.A.Dubinov, V. Ya. Aleshkin, V. E. Karasik, and M.S.Shur, arXiv:1901.00580 (2019).
- [16] M. Ryzhii, V. Ryzhii, T. Otsuji, and V. Mitin, arXiv:1901.10755 (2019).
- [17] V.Ryzhii, T.Otsuji, M.Ryzhii, D.S. Ponomarev, et al. Semicond. Sci. Technol. **33**, No.12 (2018).
- [18] V. Ryzhii, M. Ryzhii, D.S. Ponomarev, V. Leiman, V. Mitin, M.S.Shur, and T. Otsuji, J. Appl. Phys. **125**, 151608 (2019).