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Dirac plasmons in graphene/topological insulator heterostructures for THz lasers and amplifiers.

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Graphene is a two-dimensional (2D) Dirac semimetal with nontrivial topology. Its lattice chirality produces a Berry phase anomaly [1]. However, its weak spin-orbit coupling prevents it from being a topological insulator (TI). However, when graphene is in close proximity to a TI with strong spin-orbit coupling, such as Bi_2Te_3 or Bi_2Se_3, it can enter topological regimes [2, 3]. This paper proposes using a graphene-TI/semiconductor lamellar eutectic heterostructure as an electrostatically striped two-dimensional channel in Dirac plasmonic transistors. We will discuss the advantages of this heterostructure over simple graphene and/or TI 2D channels and address its potential for room-temperature, intense terahertz (THz) lasing and amplification.

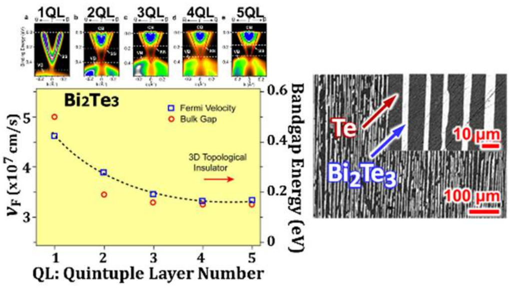

Fig. 1 QL-dependent band profile of Bi_2Te_3 (top) [4], Bi_2Te_3/Te eutectic lamellar heterostructure [5].

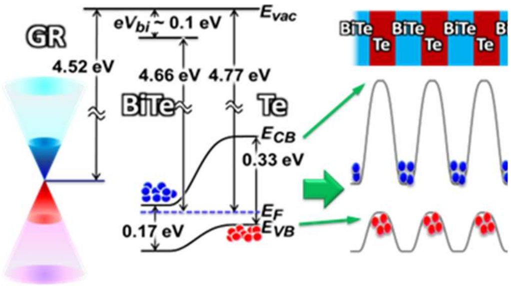

Fig. 2 Band diagrams of Bi_2Te_3/Te lamellar EuHetero [5].

First, we consider a lamellar eutectic heterostructure (EuHeter) consisting of Bi_2Te_3 TI and Te semiconductor grown via a self-organized directional solidification process (Fig. 1) [4, 5]. Each Bi_2Te_3 or Te lamellar layer has a thickness around 10 to 500 microns depending on the growth condition. Bi_2Te_3 is a topological insulator whose energy band dispersion varies depending on quintuple layer (QL) number, and $\geq$ 5 QLs of our case manifest the bulk semiconducting states rather than the surface topological states, saturating its bandgap energy around 0.17 eV [5]. The EuHetero growth process unintentionally n-type dopes the Bi2Te3 and p-type dopes the Te, resulting in repetitive p-n heterojunctions over the Bi2Te3/Te lamellar (Fig. 2) [5].

Let us consider the Bi2Te3/Te lamellar Euhetero channel asymmetric dual-grating-gate (ADGG) transistor structure under a complementary ADGG (G1 and G2) biasing and a dc drain-source biasing. The n-doped Bi_2Te_3 and p-doped Te lamellar make the planar 2D

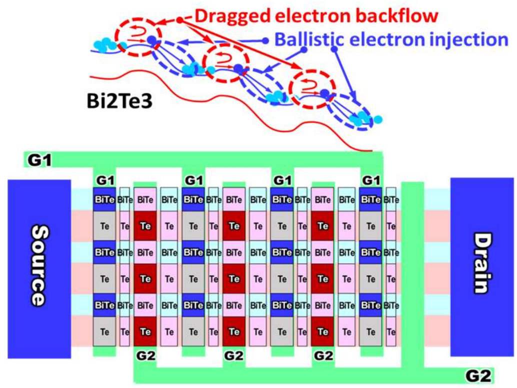

Fig. 3 Modulation-doped, striped channel formation in the graphene-Bi_2Te_3/Te EuHetero composite channel ADGG-FET [6].

channel to be electrostatically "striped-out" channel (Fig. 3) [6], which can effectively suppress excitation of oblique plasmons, a killer of cavity modes of plasmon resonance [7]. One can form striped n- or p-type channels in the Bi2Te3 or Te layers with non-uniform potential slope with cliffs along the channel, leading to the promotion of Coulomb-drag plasmonic instability and resulting resonant self-oscillation in the THz range (Fig. 3) [8].

Next, we consider a composite channel where Bi_2Te_3/Te EuHetero is stacked on monolayer graphene. The energy band offsets between graphene and Bi_2Te_3/Te allow hole injection from the p-doped Te to graphene whereas it prohibits electron injection from the n-doped Bi_2Te_3 to graphene, enabling so called "diagonal" electron/hole injection to the graphene layer. This enormously prevent from heating the injected carriers, dramatically enhancing carrier population inversion and resulting THz gain (Fig. 4) [9, 10]. We further develop an asymmetric tri-grating-gate laser transistor structure using the graphene/EuHetero lamellar composite channel that can realize an integration of a population-inverted spontaneous THz emission regions and plasmon-instability-driven coherent THz amplification regions in a single monolithic die [11]. This will open a pathway towards room-temperature, intense THz lasing and coherent, giant amplification.

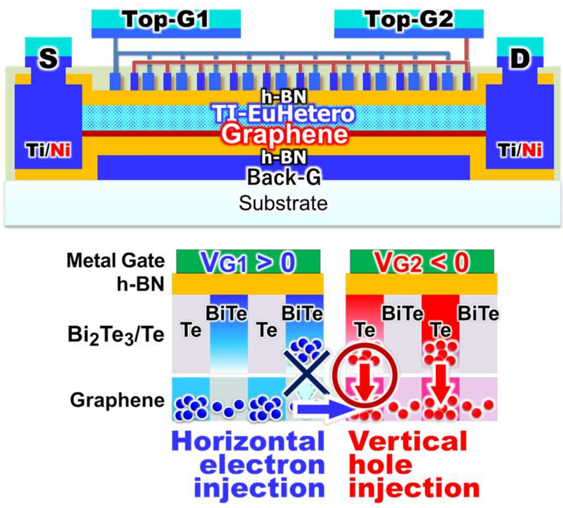

Fig. 4 Modulation-doped, striped channel formation in the graphene-Bi_2Te_3/Te EuHetero composite channel ADGG-FET [9]. Device cross sectional view (top) and diagonal doping from EuHetero to graphene (bottom) [9].

The author thanks K. Bandopadhyay, H.R. Darabian, K. Kouderis, A. Khamsavi, S. Mahdi, N. Khinevich, K. Markus, D.A. Pawlak, W. Knap, D. But, J. Kierdaszuk, J. Sitek, C. Kokacinski, M. Potemski, V. Ryzhii, S. Boubanga-Tombet, C. Tang, D. Yadav, A. Satou, K. Tamura, T. Suemitsu, H. Fukidome, M. Suemitsu, M. Ryzhii, K. Narahara, V. Mitin, and M. Shur for their contributions. He also acknowledges support by the "Centre of ExcelleNce for nanophotonicS, advancEd Materials and novel crystal growth-Based techno-LogiEs - ENSEMBLE3" project which is carried out within the 2.1 IRAP of the FNP co-financed by the EU under the European Funds for Smart Economy 2021-2027 (FENG.02.01-IP.05-0044/24), and the European Union Horizon 2020 research and innovation program Teaming for Excellence (GA. No. 857543). The publication was created as part of the project of the Minister of Science and Higher Education "Support for the activities of Centers of Excellence established in Poland under the Horizon 2020 program" (No. MEiN/2023/DIR/ 3797). He also acknowledges support by the Institute of High Pressure Physics of the Polish Academy of Sciences and the European Union through the ERC-ADVANCED grant TERAPLASM (No. 101053716).

REFERENCES

[1] M.I. Katsnelson, *Materials Today* **10** (2007) pp. 20-27.
[2] C. L. Kane et al., *Phys. Rev. Lett.*, **95**, (2005) p. 226801.
[3] I. Popov et al., *Phys. Rev. B* **90** (2014) p. 035418.
[4] Y. Li et al., *Adv. Mater.* **22**, (2010) p. 4002.
[5] K. Bandopadhyay et al., *Next Mater.* **5** (2024) p. 100252.
[6] T. Otsuji et al., Patent pending, P.452216 [WIPO ST 10/C PL452216], May 30, 2025.
[7] M. Dyakonov, *Semicond.* **42** (2008) pp. 984-988.
[8] V. Ryzhii et al., *V. Ryzhii et al., Phys. Rev. Appl.* **16** (2021) p. 014001.
[9] V. Ryzhii et al**.**, *Phys. Rev. B* **100** (2019) p. 115436.
[10] T. Otsuji et al., *Appl. Phys. Exp.* **19** (2026) p. 020103.
[11] T. Otsuji et al., to be presented at the 51st IRMMW-THz in Salt Lake City, UT, USA, Oct. 11-16, 2026.