frontiers | Frontiers in Nanotechnology

TYPE Perspective
PUBLISHED 12 December 2022
DOI 10.3389/fnano.2022.1095291

Check for updates

OPEN ACCESS

EDITED BY
Muhammad Sohail Bashir,
University of Jinan, China

REVIEWED BY
Yee Sin Ang,
Singapore University of Technology and Design, Singapore

*CORRESPONDENCE
Archit Dhingra,
archit.dhingra@uv.es

SPECIALTY SECTION
This article was submitted to Nanodevices, a section of the journal Frontiers in Nanotechnology

RECEIVED 11 November 2022
ACCEPTED 01 December 2022
PUBLISHED 12 December 2022

CITATION
Dhingra A (2022), Layered GeI_2: A wide-bandgap semiconductor for thermoelectric applications–A perspective.
Front. Nanotechnol. 4:1095291.
doi: 10.3389/fnano.2022.1095291

COPYRIGHT
© 2022 Dhingra. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Layered GeI_2: A wide-bandgap semiconductor for thermoelectric applications–A perspective

Archit Dhingra[1,2]*

[1]Department of Physics and Astronomy, University of Nebraska–Lincoln, Jorgensen Hall, Lincoln, NE, United States, [2]Carrer del Catedrátic José Beltrán Martinez, Institut de Ciència dels Materials de la Universitat de València (ICMUV), University of Valencia, Valencia, Spain

Layered GeI_2 is a two-dimensional wide-bandgap van der Waals semiconductor, which is theorized to be a promising material for thermoelectric applications. While the value of the experimentally extrapolated indirect optical bandgap of GeI_2 is found to be consistent with the existing theoretical calculations, its potential as a thermoelectric material still lacks experimental validation. In this Perspective, recent experimental efforts aimed towards investigating its dynamical properties and tuning its bandgap further, *via* intercalation, are discussed. A thorough understanding of its dynamical properties elucidates the extent of electron-phonon scattering in this system, knowledge of which is crucial in order to open pathways for future studies aiming to realize GeI_2-based thermoelectric devices.

KEYWORDS

2D materials, wide-bandgap, van der waals materials, thermoelectric, intercalation, x-ray photoemission spectroscopy, debye temperature

Introduction

Pristine layered germanium (II) iodide (GeI_2) is a two-dimensional (2D) van der Waals (vdW) material, which is predicted to be thermally stable at temperatures as high as ~ 600 K (Liu et al., 2018; Hu et al., 2020). Adding to its versatility, for potential nanodevice applications, are its: (i) low cleavage energy (~0.16 J/m^2) (Liu et al., 2018), which is even lower than that of graphite (Zacharia et al., 2004); (ii) calculated appreciable charge carrier mobilities (Liu et al., 2018); (iii) a wide-bandgap (Liu et al., 2018; Hoat et al., 2019; De Andrade Deus and De Oliveira, 2020; Hu et al., 2020; Naseri et al., 2020; Ran et al., 2020; Opoku et al., 2022), which is now experimentally verified (Dhingra et al., 2022b); and (iv) the fact that it can exist without the undesirable edge disorders (Avilov and Imamov, 1968; Urgiles et al., 1996; Liu et al., 2018) that have plagued some well-researched 2D materials (Wimmer et al., 2008; Banhart et al., 2010; Mucciolo and Lewenkopf, 2010; Wurm et al., 2011; Komsa et al., 2012; Dugaev and Katsnelson, 2013; Lo et al., 2014; Shi et al., 2014; Addou et al., 2015; Dong et al., 2015; Lin et al., 2016; Mlinar, 2017; Rosenberger et al., 2018; Blades et al., 2020; Debbarma et al., 2021). Besides being a great candidate for standalone nanodevice applications, its heterostructures have also shown some promise

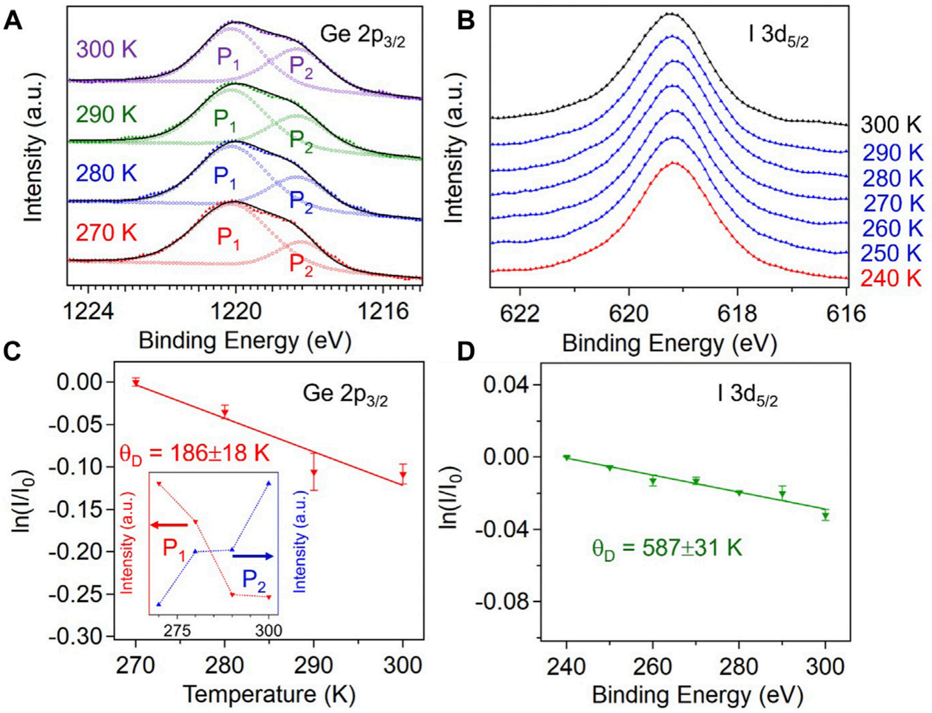

FIGURE 1
(A) Raw XPS of the Ge $2p_{3/2}$ core-level (solid markers) collected at temperatures ranging from 270 K to 300 K, along with the total fit (black line). The hollow markers show the P_1 and P_2 features. **(B)** XPS spectra of the I $3d_{5/2}$ core-level recorded at temperatures ranging from 240 K to 300 K. **(C)** Debye–Waller factor plot for the P_1 feature of the Ge $2p_{3/2}$ core-level, as well as the temperature dependence of the XPS intensities of the P_1 and P_2 components (inset). **(D)** Debye–Waller plot for the I $3d_{5/2}$ core-level (Dhingra et al., 2022b). © IOP Publishing. Reproduced with permission. All rights reserved.

for applications in development of low-power spintronic devices (Shao et al., 2021) as well as for enhancing photocatalytic hydrogen generation performance (Opoku et al., 2022).

In this Perspective, some recent efforts that were aimed towards experimental investigation of the understudied, but highly promising, pristine 2D layered GeI_2 are discussed. The main purpose of this article is to comment on the dynamical stability of the 2D layered GeI_2, and the intercalation-induced tuning of its bandgap, in the context of its potential as a wide-bandgap thermoelectric material.

Dynamical behavior of the layered GeI_2: What do temperature variations do to GeI_2?

A fundamental understanding of the effects of temperature variation on any material is indispensable if that material is to be used for thermoelectric applications. Therefore, in this subsection the dynamical behavior of the pristine 2D layered GeI_2 is described and discussed. The deterrent effects of the thermal motion of atoms on the physical and electronic properties of materials are well-known (Körmann et al., 2017; Randle et al., 2018; Dhingra et al., 2020; 2021a; 2021b). One certain way to quantify the extent of electron-phonon scattering (or the effects of thermal motion of atoms) in a material is to ascertain its Debye (or effective Debye) temperature. In this regard, temperature dependent x-ray photoemission spectroscopy (XPS) is routinely exploited to determine a system's effective Debye temperature (Clarke, 1985; Borca et al., 2000; McHale et al., 2011; Evans et al., 2018; Dhingra et al., 2020; 2021a; 2021b).

Figures 1A, B show the temperature dependent XPS spectra of the Ge $2p_{3/2}$ core-level and the I $3d_{5/2}$ core-level, respectively. The effective Debye temperatures of the Ge $2p_{3/2}$ component closer to the surface (the P_1 feature of the Ge $2p_{3/2}$ core-level) and the I $3d_{5/2}$ core-level, as extracted from the linear fits to the Debye–Waller plots in Figures 1C, D, are found to be 186 ± 18 K and 587 ± 31 K, respectively (Dhingra et al., 2022b). It is worth mentioning that, unlike the observed temperature dependence of the photoemission intensities of the P_1 feature of the Ge $2p_{3/2}$ core-level and the I $3d_{5/2}$ core-level, the XPS intensity of the P_2 feature of the Ge $2p_{3/2}$ core-level is found to increase with increasing temperature (see inset of Figure 1C). Such a direct

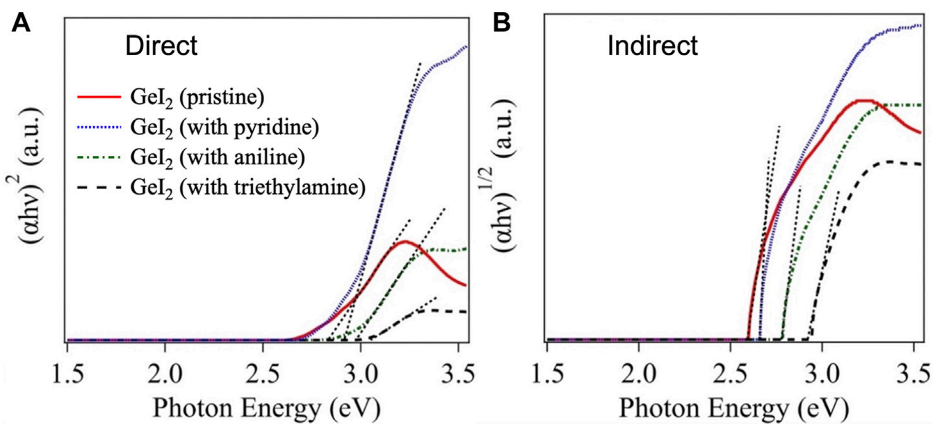

FIGURE 2
Tauc plots for extrapolation of **(A)** direct and **(B)** indirect band gaps of the pristine and intercalated GeI_2 systems. Reprinted by permission from Springer Nature (Dhingra et al., 2022a), 2022.

relationship between the photoemission intensity of the P_2 component of the Ge $2p_{3/2}$ core-level and temperature implies segregation of germanium in the subsurface (or selvedge) of GeI_2 (Dhingra et al., 2022b).

Effects of intercalation: can the bandgap of GeI_2 be widened further?

Over the years, intercalation of various 2D materials has resulted in widening of their bandgaps (Eknapakul et al., 2014; Song et al., 2015; Xiong et al., 2015; Wan et al., 2016; Feng et al., 2019). While the pristine GeI_2 already has a wide-bandgap, intercalating it with easily synthesizable organic molecules to widen its bandgap further is bound to amplify its utility for low-dimensional high-temperature thermoelectric and optoelectronic applications; and this is exactly what was demonstrated in a recent study (Dhingra et al., 2022a).

Figure 2 shows the Tauc plots through which the direct (Figure 2A) and indirect (Figure 2B) bandgaps of pristine and intercalated GeI_2 can be extrapolated (Tauc et al., 1966; Wood and Tauc, 1972). From Figure 2, it is clear that both the direct and indirect optical bandgaps of the pristine GeI_2 are in agreement with the ones reported elsewhere (Dhingra et al., 2022b), and the extrapolated direct (indirect) optical bandgaps upon intercalation with the organic molecules, namely: pyridine, aniline, and triethylamine, are found to lie somewhere between 2.9 (2.66)–3.1 (2.92) eV.

Discussion

Theoretically, layered GeI_2 is a low-dimensional material that is waiting to get exploited for thermoelectric applications (Hu et al., 2020; Lu and Guan, 2022); nevertheless, there are no experiments to confirm the same. The limited experimentally obtained information that we do have on this exciting nanomaterial suggests that the surface of the layered GeI_2 is not stable enough under ambient conditions, and is prone to a large amount of phonon scattering since the effective Debye temperature of the surface is way less than the room temperature (Dhingra et al., 2022b). However, if the complexities encountered at the surface of this material are addressed by depositing a thin layer of a stiff oxide, as has been done for some other quasi-1D materials (Lipatov et al., 2015; Dhingra, 2022), then it may well be possible to realize its potential as a thermoelectric nanomaterial. A stable GeI_2 surface with suppressed phonon scattering, when taken together with the ease with which the bandgap of GeI_2 can be widened further (Dhingra et al., 2022a), will augment its versatility for high-temperature thermoelectric applications. Finally, it must be noted that as is the case when it comes to forming contacts with most 2D materials (S. Schulman et al., 2018; Ang et al., 2021; Zheng et al., 2021; Dhingra et al., 2020a; Dhingra et al., 2021c; Dhingra et al., 2022c; Dhingra et al., 2022d), forming Ohmic contacts to GeI_2 may not be trivial; especially because the germanium rich surface could adversely affect the contact potentials for GeI_2-based nanodevices (Dhingra et al., 2022b). This Perspective, thus, acts as a guide for future studies dealing with the GeI_2-based thermoelectric nanodevices.

Data availability statement

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author.

Author contributions

AD wrote the whole manuscript.

Funding

This work was supported by the National Science Foundation through EPSCoR RII Track-1: Emergent Quantum Materials and Technologies (EQUATE), Award No. OIA-2044049; and by the Ministerio de Ciencia e Innovación, which is part of AEI, through the project PID2020-112507GB-I00 (Novel quantum states in heterostructures of 2D materials).

Acknowledgments

The author is grateful to Peter A. Dowben for useful discussions.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Addou, R., Colombo, L., and Wallace, R. M. (2015). Surface defects on natural MoS_2. *ACS Appl. Mat. Interfaces* 7, 11921–11929. doi:10.1021/acsami.5b01778

Ang, Y. S., Cao, L., and Ang, L. K. (2021). Physics of electron emission and injection in two-dimensional materials: Theory and simulation. *InfoMat* 3, 502–535. doi:10.1002/inf2.12168

Avilov, A. S., and Imamov, R. M. (1968). Electron-diffraction study of germanium diiodide. *Kristallografiya* 13.

Banhart, F., Kotakoski, J., and Krasheninnikov, A. V. (2010). Structural defects in graphene. *ACS Nano* 5, 26–41. doi:10.1021/NN102598M

Blades, W. H., Frady, N. J., Litwin, P. M., McDonnell, S. J., and Reinke, P. (2020). Thermally induced defects on WSe_2. *J. Phys. Chem. C* 124, 15337–15346. doi:10.1021/ACS.JPCC.0C04440

Borca, C. N., Komesu, T., Jeong, H.-K., Dowben, P. A., Ristoiu, D., Hordequin, C., et al. (2000). Effective surface Debye temperature for NiMnSb(100) epitaxial films. *Appl. Phys. Lett.* 77, 88–90. doi:10.1063/1.126886

Clarke, L. J. (1985). *Surface crystallography: An introduction to low energy electron diffraction*. John Wiley & Sons.

De Andrade Deus, D. P., and De Oliveira, I. S. S. (2020). Tuning the Schottky barrier height in graphene/monolayer-GeI_2 van der Waals heterostructure. *J. Phys. Condens. Matter* 32, 355501. doi:10.1088/1361-648X/ab8bf8

Debbarma, R., Nguyen, N. H. L., and Berry, V. (2021). Defect guided conduction in graphene-derivatives and MoS_2: Two-dimensional nanomaterial models. *Appl. Mat. Today* 23, 101072. doi:10.1016/J.APMT.2021.101072

Dhingra, A., Blair, R. G., and Dowben, P. A. (2022a). Effects of intercalation on bandgap of pristine two-dimensional layered GeI_2. *MRS Adv.* 7, 763–765. doi:10.1557/s43580-022-00302-6

Dhingra, A., Galiy, P. V., Wang, L., Vorobeva, N. S., Lipatov, A., Torres, A., et al. (2020a). Surface termination and Schottky-barrier formation of In_4Se_3(001). *Semicond. Sci. Technol.* 35, 065009. doi:10.1088/1361-6641/ab7e45

Dhingra, A., Lipatov, A., Loes, M. J., Sinitskii, A., and Dowben, P. A. (2021a). Nonuniform Debye temperatures in quasi-one-dimensional transition-metal trichalcogenides. *ACS Mat. Lett.* 3, 414–419. doi:10.1021/acsmaterialslett.1c00094

Dhingra, A., Lipatov, A., Loes, M. J., Abourahma, J., Pink, M., Sinitskii, A., et al. (2022c). Effect of Au/HfS_3 interfacial interactions on properties of HfS_3-based devices. *Phys. Chem. Chem. Phys.* 24, 14016–14021. doi:10.1039/D2CP01254E

Dhingra, A., Lipatov, A., Lu, H., Chagoya, K., Dalton, J., Gruverman, A., et al. (2022b). Surface and dynamical properties of GeI_2. *2D Mat.* 9, 025001. doi:10.1088/2053-1583/ac4715

Dhingra, A., Marzouk, Z. G., Mishra, E., Galiy, P. V., Nenchuk, T. M., and Dowben, P. A. (2020). Indium segregation to the selvedge of In_4Se_3 (001). *Phys. B Condens. Matter* 593, 412280. doi:10.1016/j.physb.2020.412280

Dhingra, A., Nikonov, D. E., Lipatov, A., Sinitskii, A., and Dowben, P. A. (2022d). What happens when transition metal trichalcogenides. *J. Mater. Res.*. doi:10.1557/s43578-022-00744-6

Dhingra, A. (2022). *Physical and electronic properties of two-dimensional layered materials: In_4Se_3, TiS_3, ZrS_3, HfS_3, and GeI_2.*

Dhingra, A., Sando, D., Lu, P.-S., Marzouk, Z. G., Nagarajan, V., and Dowben, P. A. (2021b). X-ray photoemission studies of $BiInO_3$: Surface termination and effective Debye temperature. *J. Appl. Phys.* 130, 025304. doi:10.1063/5.0057556

Dhingra, A., Lipatov, A., Sinitskii, A., and Dowben, P. A. (2021c). Complexities at the Au/ZrS_3(001) interface probed by x-ray photoemission spectroscopy. *J. Phys.: Condens. Matter* 33, 434001. doi:10.1088/1361-648X/ac16f8

Dong, L., Wang, J., Namburu, R., O'Regan, T. P., Dubey, M., and Dongare, A. M. (2015). Edge effects on band gap energy in bilayer 2H-MoS_2 under uniaxial strain. *J. Appl. Phys.* 117, 244303. doi:10.1063/1.4922811

Dugaev, V. K., and Katsnelson, M. I. (2013). Edge scattering of electrons in graphene: Boltzmann equation approach to the transport in graphene nanoribbons and nanodisks. *Phys. Rev. B* 88, 235432. doi:10.1103/PhysRevB.88.235432

Eknapakul, T., King, P. D. C., Asakawa, M., Buaphet, P., He, R.-H., Mo, S.-K., et al. (2014). Electronic structure of a quasi-freestanding MoS_2 monolayer. *Nano Lett.* 14, 1312–1316. doi:10.1021/nl4042824

Evans, P. E., Pink, M., Zhumekenov, A. A., Hao, G., Losovyj, Y., Bakr, O. M., et al. (2018). Rotationally free and rigid sublattices of the single crystal perovskite $CH_3NH_3PbBr_3$(001): The case of the lattice polar liquid. *J. Phys. Chem. C* 122, 25506–25514. doi:10.1021/acs.jpcc.8b08994

Feng, N., Meng, R., Zu, L., Feng, Y., Peng, C., Huang, J., et al. (2019). A polymer-direct-intercalation strategy for MoS_2/carbon-derived heteroaerogels with ultrahigh pseudocapacitance. *Nat. Commun.* 10, 1372. doi:10.1038/s41467-019-09384-7

Hoat, D. M., Vu, T. V., Obeid, M. M., and Jappor, H. R. (2019). Tuning the electronic structure of 2D materials by strain and external electric field: Case of GeI_2 monolayer. *Chem. Phys.* 527, 110499. doi:10.1016/j.chemphys.2019.110499

Hu, Y. F., Yang, J., Yuan, Y. Q., and Wang, J. W. (2020). GeI_2 monolayer: A model thermoelectric material from 300 to 600 K. *Philos. Mag.* 100, 782–796. doi:10.1080/14786435.2019.1699670

Komsa, H.-P., Kotakoski, J., Kurasch, S., Lehtinen, O., Kaiser, U., and Krasheninnikov, A. V. (2012). Two-dimensional transition metal dichalcogenides under electron irradiation: Defect production and doping. *Phys. Rev. Lett.* 109, 035503. doi:10.1103/PhysRevLett.109.035503

Körmann, F., Ikeda, Y., Grabowski, B., and Sluiter, M. H. F. (2017). Phonon broadening in high entropy alloys. *npj Comput. Mat.* 3, 36. doi:10.1038/s41524-017-0037-8

Lin, Z., Carvalho, B. R., Kahn, E., Lv, R., Rao, R., Terrones, H., et al. (2016). Defect engineering of two-dimensional transition metal dichalcogenides. *2D Mat.* 3, 022002. doi:10.1088/2053-1583/3/2/022002

Lipatov, A., Wilson, P. M., Shekhirev, M., Teeter, J. D., Netusil, R., and Sinitskii, A. (2015). Few-layered titanium trisulfide (TiS_3) field-effect transistors. *Nanoscale* 7, 12291–12296. doi:10.1039/c5nr01895a

Liu, C. S., Yang, X., Le, Liu, J., and Ye, X. J. (2018). Exfoliated monolayer GeI_2: Theoretical prediction of a wide-band gap semiconductor with tunable half-metallic ferromagnetism. *J. Phys. Chem. C* 122, 22137–22142. doi:10.1021/acs.jpcc.8b05529

Lo, S.-T., Klochan, O., Liu, C.-H., Wang, W.-H., Hamilton, A. R., and Liang, C.-T. (2014). Transport in disordered monolayer MoS_2 nanoflakes—Evidence for inhomogeneous charge transport. *Nanotechnology* 25, 375201. doi:10.1088/0957-4484/25/37/375201

Lu, N., and Guan, J. (2022). Thermoelectric performance of XI_2 (X = Ge, Sn, Pb) bilayers. *Chin. Phys. B* 31, 047201. doi:10.1088/1674-1056/ac474C

McHale, S. R., McClory, J. W., Petrosky, J. C., Wu, J., Palai, R., Dowben, P. A., et al. (2011). The effective surface Debye temperature of Yb:GaN. *Mat. Lett.* 65, 1476–1478. doi:10.1016/j.matlet.2011.02.042

Mlinar, V. (2017). Electronic and optical properties of nanostructured MoS_2 materials: Influence of reduced spatial dimensions and edge effects. *Phys. Chem. Chem. Phys.* 19, 15891–15902. doi:10.1039/C7CP03229C

Mucciolo, E. R., and Lewenkopf, C. H. (2010). Disorder and electronic transport in graphene. *J. Phys. Condens. Matter* 22, 273201. doi:10.1088/0953-8984/22/27/273201

Naseri, M., Hoat, D. M., Salehi, K., and Amirian, S. (2020). Theoretical prediction of 2D XI_2 (X=Si, Ge, Sn, Pb) monolayers by density functional theory. *J. Mol. Graph. Model.* 95, 107501. doi:10.1016/j.jmgm.2019.107501

Opoku, F., Oppong, S. O.-B., Asare-Donkor, N. K., Akoto, O., and Adimado, A. A. (2022). Enhancing the photocatalytic hydrogen generation performance and strain regulation of the vertical GeI_2/C_2N van der Waals heterostructure: Insights from first-principles study. *Energy Adv.* 1, 146–158. doi:10.1039/D1YA00047K

Ran, R., Hu, C.-E., Cheng, Y., Chen, X.-R., and Ji, G.-F. (2020). First-principles study of structures, elastic and optical properties of single-layer metal iodides under strain. *Z. für Naturforsch. A* 75, 877–886. doi:10.1515/zna-2020-0157

Randle, M., Lipatov, A., Kumar, A., Kwan, C.-P., Nathawat, J., Barut, B., et al. (2018). Gate-controlled metal–insulator transition in TiS_3 nanowire field-effect transistors. *ACS Nano* 13, 803–811. doi:10.1021/acsnano.8b08260

Rosenberger, M. R., Chuang, H.-J., McCreary, K. M., Li, C. H., and Jonker, B. T. (2018). Electrical characterization of discrete defects and impact of defect density on photoluminescence in monolayer WS_2. *ACS Nano* 12, 1793–1800. doi:10.1021/ACSNANO.7B08566

Schulman, S., Arnold, D., J., and Das, S. (2018). Contact engineering for 2D materials and devices. *Chem. Soc. Rev.* 47, 3037–3058. doi:10.1039/C7CS00828G

Shao, D.-F., Ding, J., Gurung, G., Zhang, S.-H., and Tsymbal, E. Y. (2021). Interfacial crystal Hall effect reversible by ferroelectric polarization. *Phys. Rev. Appl.* 10, 024057. doi:10.1103/PhysRevApplied.15.024057

Shi, Y.-J., Lan, J., Ye, E.-J., Sui, W.-Q., and Zhao, X. (2014). Four-terminal impedance of a graphene nanoribbon based structure. *Eur. Phys. J. B* 87, 251. doi:10.1140/epjb/e2014-50321-0

Song, S. H., Kim, B. H., Choe, D.-H., Kim, J., Kim, D. C., Lee, D. J., et al. (2015). Bandgap widening of phase quilted, 2D MoS_2 by oxidative intercalation. *Adv. Mat.* 27, 3152–3158. doi:10.1002/adma.201500649

Tauc, J., Grigorovici, R., and Vancu, A. (1966). Optical properties and electronic structure of amorphous germanium. *Phys. Stat. Sol.* 15, 627–637. doi:10.1002/pssb.19660150224

Urgiles, E., Melo, P., and Coleman, C. C. (1996). Vapor reaction growth of single crystal GeI_2. *J. Cryst. Growth* 165, 245–249. doi:10.1016/0022-0248(96)00193-5

Wan, J., Lacey, S. D., Dai, J., Bao, W., Fuhrer, M. S., and Hu, L. (2016). Tuning two-dimensional nanomaterials by intercalation: Materials, properties and applications. *Chem. Soc. Rev.* 45, 6742–6765. doi:10.1039/C5CS00758E

Wimmer, M., Adagideli, İ., Berber, S., Tománek, D., and Richter, K. (2008). Spin currents in rough graphene nanoribbons: Universal fluctuations and spin injection. *Phys. Rev. Lett.* 100, 177207. doi:10.1103/PhysRevLett.100.177207

Wood, D. L., and Tauc, J. (1972). Weak absorption tails in amorphous semiconductors. *Phys. Rev. B* 5, 3144–3151. doi:10.1103/PhysRevB.5.3144

Wurm, J., Richter, K., and Adagideli, İ. (2011). Edge effects in graphene nanostructures: From multiple reflection expansion to density of states. *Phys. Rev. B* 84, 075468. doi:10.1103/PhysRevB.84.075468

Xiong, F., Wang, H., Liu, X., Sun, J., Brongersma, M., Pop, E., et al. (2015). Li intercalation in MoS_2: *In situ* observation of its dynamics and tuning optical and electrical properties. *Nano Lett.* 15, 6777–6784. doi:10.1021/acs.nanolett.5b02619

Zacharia, R., Ulbricht, H., and Hertel, T. (2004). Interlayer cohesive energy of graphite from thermal desorption of polyaromatic hydrocarbons. *Phys. Rev. B* 69, 155406. doi:10.1103/PhysRevB.69.155406

Zheng, Y., Gao, J., Han, C., and Chen, W. (2021). Ohmic contact engineering for two-dimensional materials. *Cell. Rep. Phys. Sci.* 2, 100298. doi:10.1016/j.xcrp.2020.100298