APL Materials

Fundamentals and applications of mixed-dimensional heterostructures

Cite as: APL Mater. **10**, 060402 (2022); https://doi.org/10.1063/5.0097804
Submitted: 02 May 2022 • Accepted: 31 May 2022 • Published Online: 30 June 2022

Kyusang Lee, Xiangfeng Duan, Mark C. Hersam, et al.

Fundamentals and applications of mixed-dimensional heterostructures

Cite as: APL Mater. 10, 060402 (2022); doi: 10.1063/5.0097804
Submitted: 2 May 2022 • Accepted: 31 May 2022 •
Published Online: 30 June 2022

View Online Export Citation CrossMark

Kyusang Lee,[1] Xiangfeng Duan,[2] Mark C. Hersam,[3] and Jeehwan Kim[4,a)]

AFFILIATIONS

[1] Department of Electrical and Computer Engineering and Department of Materials Science and Engineering, University of Virginia, Charlottesville, Virginia 22903, USA
[2] Department of Chemistry and Biochemistry and California NanoSystems Institute, University of California, Los Angeles, California 90095, USA
[3] Department of Materials Science and Engineering, Department of Chemistry, and Department of Electrical and Computer Engineering, Northwestern University, Evanston, Illinois 60208-3118, USA
[4] Department of Mechanical Engineering, Research Laboratory of Electronics and Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

Note: This paper is part of the Special Topic on Fundamentals and Applications of Mixed-Dimensional Heterostructures.
[a)] **Author to whom correspondence should be addressed:** jeehwan@mit.edu

INTRODUCTION

Mixed-dimensional heterostructures formed by combining materials of different dimensionality offer diverse multi-functionality that cannot be otherwise obtained by pure 0D, 1D, 2D, or 3D materials.[1–6] The discontinuous changes in the energy dependence of the density of states and the degree of electrostatic screening across mixed-dimensional heterointerfaces substantially alter the electrical, magnetic, optical, and thermal properties, thereby presenting new and/or improved functionalities in applied technologies.[7–12] This special issue presents the latest research results for mixed-dimensional heterostructures, including synthesis, characterization, theory, and applications in electronics and photonics. Highlights from this special issue are presented below.

SPECIAL ISSUE HIGHLIGHTS

The development of growth and fabrication methods for mass-transferable and position-controlled microarrays of semiconductors enables effective heterogeneous integration without additional assembly processes. Toward this end, Jin *et al.* demonstrated site-selective remote epitaxial growth of mechanically transferable ZnO microrod and microdisk arrays via hydrothermal growth.[13] To define the growth sites, a patterned mask layer is formed on 2D material-coated substrates. Then, remote epitaxy is conducted, which allows growth of ZnO microarrays only on the patterned areas. The weak van der Waals (vdW) interaction between the resulting microrods and the graphene surface allows facile mechanical lift-off of the ZnO microarrays and transfer onto a separate host substrate. In related work, Sundaram *et al.* reviewed their recent progress in vdW metal organic vapor phase epitaxy (MOVPE) of wafer-scale 2D layered hexagonal boron nitride (h-BN) and III-N materials.[14] This monolithic growth process allows for mechanical transfer of GaN-based devices off of the h-BN surface to various support wafers. This large-scale vdW h-BN MOVPE enhances III-N device functionality and improves III-N processing technology toward heterogeneous integration. Similarly, Kim *et al.* showed improved growth and exfoliation yield of remote epitaxy by utilizing a novel atomic layer etching (ALE) technique.[15] In particular, they first grew multilayer graphene directly onto $SrTiO_3$ substrates, followed by layer-by-layer ALE of the graphene layers down to one to two layers. Remote epitaxy on this substrate showed higher yield in terms of the exfoliated area due to the absence of defects (tears, wrinkles, and contaminants) when compared with graphene transferred from another substrate, such as SiC or Cu foil. This study highlights that direct growth of graphene on the desired substrate is key for lab-to-fab transition and commercialization of the remote epitaxy technique.

Mixed-dimensional heterostructures provide new physical properties and phenomena that enable unconventional electronic functions. To realize 2D/3D heterostructures for next-generation electronics, Ma *et al.* demonstrated remote epitaxy of high-quality 3D oxide materials on 2D MoS_2.[16] Meanwhile, Hong *et al.* reviewed growth and fabrication methods for 1D semiconductor nanostructures on 2D substrates.[17] In this case, the 1D nanostructures exhibit excellent materials characteristics, including high charge carrier mobility and long-term stability, while the 2D layers show high optical transparency and mechanical flexibility in addition to superior electrical characteristics. With this unique combination of properties, these 1D/2D heterostructures have been effectively employed for high-performance electronic and optoelectronic devices, including transistors, light-emitting devices, photodetectors, and pressure sensors. In another example, Turker *et al.* described the operating principles, materials characteristics, and heterostructure considerations for 2D/3D hot electron transistors (HETs).[18] The integration of 2D materials with 3D structures allows vertical HETs to achieve ballistic transport with cutoff frequencies in excess of 15 THz since the intrinsic limitations of lateral devices, such as lithography of the gate, short-channel effects, and velocity saturation, are circumvented.

The use of 2D materials as contacts for low-dimensional semiconductor devices has attracted significant attention since the vdW interface minimizes Fermi level pinning. For example, Kim *et al.* demonstrated efficient charge transfer across a 2D/semiconductor heterointerface between ZnO and $NbSe_2$ prepared using hydrothermal processing.[19] The heterojunction between ZnO and $NbSe_2$ lowers the barrier height for charge injection, and the conductive surface states of ZnO provide an additional conduction channel, resulting in Ohmic behavior that is consistent with density functional theory (DFT) calculations. In another DFT study, Zhou *et al.* elucidated the electronic structure and energy level alignment of 0D metal phthalocyanine (MPc) molecules on 2D MoS_2.[20] Screened range-separated hybrid (SRSH) functions allow the electronic structure of mixed-dimensional heterojunctions comprised of 2D materials and 0D constructs to be calculated in a manner that accounts for the effects of the heterogeneous dielectric environment.

Other applications for mixed-dimensional heterostructures include nonlinear optics and catalysis. For instance, Sheridan *et al.* performed nonlinear optical spectroscopy on graphene nanoribbons (GNRs) using nanoscale junctions defined at the $LaAlO_3/SrTiO_3$ interface, thus revealing a strong, gate-tunable second and third harmonic response, as well as enhanced extinction of visible to near-infrared light.[21] From the perspective of catalysis, Ling *et al.* facilitated the hydrogen evolution reaction (HER) by plasma-treating the edges of semimetallic layered tungsten ditelluride (WTe_2) using a microcell device.[22] Atomic defects, substitutions, and new chemical bonds were locally induced on the basal plane and edges of WTe_2 by mild plasma treatment, leading to catalytically activated WTe_2. Microcell device studies show that the plasma-treated edges exhibit considerably improved electrocatalytic activity for HER, including an attenuated overpotential and reduced Tafel slope, compared with pristine WTe_2.

CONCLUSION

In conclusion, this special issue covers a broad range of fundamental and applied topics related to heterogeneous integration of mixed-dimensional materials. The high degree of interdisciplinarity in this work implies that it will be of broad interest to physicists, chemists, and engineers who are seeking to understand and utilize the combined benefits of materials from multiple low-dimensional classes. As this field is still in its infancy, we anticipate that this special issue will help inspire and guide future efforts to move mixed-dimensional heterostructures from the research laboratory to large-scale commercial applications.

ACKNOWLEDGMENTS

K.L. acknowledges support from the National Science Foundation (Grant No. NSF ECCS-1942868). In addition, J.K. and K.L. acknowledge support from the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy (EERE) under the Solar Energy Technologies Office (Grant No. DE-EE0008588). M.C.H. acknowledges support from the National Science Foundation Materials Research Science and Engineering Center at Northwestern University (Grant No. NSF DMR-1720139). X.D. acknowledges support from the Office of Naval Research through Grant No. N00014-18-1-2707.

REFERENCES

[1] D. Jariwala, T. J. Marks, and M. C. Hersam, Nat. Mater. **16**, 170 (2017).
[2] P. Wang, C. Jia, Y. Huang, and X. Duan, Matter **4**, 552 (2021).
[3] S.-H. Bae, H. Kum, W. Kong, Y. Kim, C. Choi, B. Lee, P. Lin, Y. Park, and J. Kim, Nat. Mater. **18**, 550 (2019).
[4] J. Kim, C. Bayram, H. Park, C.-W. Cheng, C. Dimitrakopoulos, J. A. Ott, K. B. Reuter, S. W. Bedell, and D. K. Sadana, Nat. Commun. **5**, 4836 (2014).
[5] Y. Kim, S. S. Cruz, K. Lee, B. O. Alawode, C. Choi, Y. Song, J. M. Johnson, C. Heidelberger, W. Kong, S. Choi, K. Qiao, I. Almansouri, E. A. Fitzgerald, J. Kong, A. M. Kolpak, J. Hwang, and J. Kim, Nature **544**, 340 (2017).
[6] H. S. Kum, H. Lee, S. Kim, S. Lindemann, W. Kong, K. Qiao, P. Chen, J. Irwin, J. H. Lee, S. Xie, S. Subramanian, J. Shim, S.-H. Bae, C. Choi, L. Ranno, S. Seo, S. Lee, J. Bauer, H. Li, K. Lee, J. A. Robinson, C. A. Ross, D. G. Schlom, M. S. Rzchowski, C.-B. Eom, and J. Kim, Nature **578**, 75 (2020).
[7] Y. Liu, Y. Huang, and X. Duan, Nature **567**, 323 (2019).
[8] S. H. Amsterdam, T. J. Marks, and M. C. Hersam, J. Phys. Chem. Lett. **12**, 4543 (2021).
[9] S. Padgaonkar, J. N. Olding, L. J. Lauhon, M. C. Hersam, and E. A. Weiss, Acc. Chem. Res. **53**, 763 (2020).
[10] Y. Liu, N. O. Weiss, X. Duan, H.-C. Cheng, Y. Huang, and X. Duan, Nat. Rev. Mater. **1**, 16042 (2016).
[11] J. Shim, S.-H. Bae, W. Kong, D. Lee, K. Qiao, D. Nezich, Y. J. Park, R. Zhao, S. Sundaram, X. Li, H. Yeon, C. Choi, H. Kum, R. Yue, G. Zhou, Y. Ou, K. Lee, J. Moodera, X. Zhao, J.-H. Ahn, C. Hinkle, A. Ougazzaden, and J. Kim, Science **362**, 665 (2018).
[12] W. Kong, H. Li, K. Qiao, Y. Kim, K. Lee, Y. Nie, D. Lee, T. Osadchy, R. J. Molnar, D. K. Gaskill, R. L. Myers-Ward, K. M. Daniels, Y. Zhang, S. Sundram, Y. Yu, S.-h. Bae, S. Rajan, Y. Shao-Horn, K. Cho, A. Ougazzaden, J. C. Grossman, and J. Kim, Nat. Mater. **17**, 999 (2018).
[13] D. K. Jin, J. Choi, J. Jeong, B. K. Kang, Q. Wang, W. S. Yang, M. J. Kim, and Y. J. Hong, APL Mater. **9**, 051102 (2021).
[14] S. Sundaram, P. Vuong, A. Mballo, T. Ayari, S. Karrakchou, G. Patriarche, P. L. Voss, J. P. Salvestrini, and A. Ougazzaden, APL Mater. **9**, 061101 (2021).
[15] K. S. Kim, J. E. Kang, P. Chen, S. Kim, J. Ji, G. Y. Yeom, J. Kim, and H. S. Kum, APL Mater. **10**, 041105 (2022).
[16] C.-H. Ma, L.-S. Lu, H. Song, J.-W. Chen, P.-C. Wu, C.-L. Wu, R. Huang, W.-H. Chang, and Y.-H. Chu, APL Mater. **9**, 051115 (2021).
[17] Y. J. Hong, R. K. Saroj, W. I. Park, and G.-C. Yi, APL Mater. **9**, 060907 (2021).
[18] F. Turker, S. Rajabpour, and J. A. Robinson, APL Mater. **9**, 081103 (2021).

[19]Y. Kim, R. Tutchton, R. Liu, S. Krylyuk, J.-X. Zhu, A. V. Davydov, Y. J. Hong, and J. Yoo, APL Mater. **9**, 091107 (2021).
[20]Q. Zhou, Z.-F. Liu, T. J. Marks, and P. Darancet, APL Mater. **9**, 121112 (2021).
[21]E. Sheridan, G. Li, M. Sarker, S. Hao, K.-T. Eom, C.-B. Eom, A. Sinitskii, P. Irvin, and J. Levy, APL Mater. **9**, 071101 (2021).
[22]N. Ling, S. Zheng, Y. Lee, M. Zhao, E. Kim, S. Cho, and H. Yang, APL Mater. **9**, 061108 (2021).