

Bridging Material Design and Intelligent Systems in Low-Dimensional Materials for Electronics and Sensing

Hu Li ^{1,2,3,*}  and Klaus Leifer ⁴ 

¹ Shandong Key Laboratory of Next-Generation Semiconductor Technology and Systems, School of Integrated Circuits, Shandong University, Jinan 250101, China

² Xinjiang Research Institute, Shandong University, Changji 831100, China

³ Shenzhen Research Institute, Shandong University, Shenzhen 518057, China

⁴ Ångström Laboratory, Department of Materials Science and Engineering, Uppsala University, 75121 Uppsala, Sweden; klaus.leifer@angstrom.uu.se

* Correspondence: hu.li@sdu.edu.cn

Low-dimensional materials have become central to the development of emerging electronic, optoelectronic, sensing, energy-storage, and information-processing technologies. When one or more dimensions of a material are reduced to the micro- or nanoscale, its electronic structure, surface chemistry, charge transport, optical response, and mechanical behavior can differ substantially from those of its bulk counterpart [1,2]. These characteristics provide opportunities to engineer devices with high sensitivity, low power consumption, rapid response, mechanical flexibility, and novel functionalities [3].

The progress of low-dimensional electronics is not based on a single class of materials or devices, and it is driven by the convergence of semiconductor physics, surface and interface chemistry, nanofabrication, signal processing, computational modeling and more. Graphene and other two-dimensional materials provide atomically thin channels and highly accessible surfaces; one-dimensional semiconductor structures offer anisotropic transport and quantum confinement; nanostructured metal oxides provide abundant adsorption sites for chemical sensing; perovskites exhibit pressure-dependent electronic and optical properties; and porous crystalline frameworks enable the selective capture and detection of a wide variety of analytes. At the system level, electronic noses, neuromorphic devices, and intelligent sensing platforms illustrate how low-dimensional materials can be combined with advanced algorithms and unconventional computing architectures.

This Special Issue, titled “Advances in Low-Dimensional Materials for Electronics and Sensing Applications”, brings together 12 contributions that reflect this diversity. These articles address the fundamental properties of low-dimensional materials, their synthesis and structural regulation, gas and environmental sensing, device integration, neuromorphic computing, and energy storage. Together, they illustrate a research pathway extending from the atomic-scale understanding and controlled preparation of materials to their integration into functional devices and intelligent systems.

Understanding the relationship between structure and electronic behavior is essential for designing low-dimensional materials for sensing and electronic applications. Huang et al. investigated the structural and carrier-transport properties of inorganic perovskite CsPbI₃ under pressure using density functional theory and real-time time-dependent density functional theory (contribution 1). Their calculations showed that the lattice constant decreases approximately linearly with increasing pressure, while the hot-carrier cooling pathway and transition dipole moment are also modified. The calculated increase in electrical conductivity under pressure provides a microscopic basis for considering CsPbI₃



Received: 16 July 2026

Accepted: 16 July 2026

Published: 17 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

as a potential piezoresistive material. This study illustrates how first-principles modeling can reveal pressure-dependent mechanisms that are difficult to isolate experimentally and can guide the development of perovskite-based pressure and strain sensors.

Zhao et al. provided a broad review of two-dimensional materials for optoelectronic applications (contribution 2). The review covers graphene, transition-metal dichalcogenides, black phosphorus, MXenes, hexagonal boron nitride, and related materials, emphasizing their morphology, crystal structure, optical characteristics, synthesis routes, and device applications. The article demonstrates that the appeal of two-dimensional materials originates from the combination of strong light–matter interactions, tunable band structures, high carrier mobility, mechanical flexibility, and compatibility with heterostructure engineering. It also identifies recurring challenges, including material stability, controllable large-area synthesis, interface quality, and reproducible device fabrication.

The dimensionality of semiconductor structures can also be controlled during epitaxial growth. Muthuraj et al. explored the metal–organic chemical vapor deposition of N-polar InN quantum dashes and quantum-wire-like structures on miscut substrates (contribution 3). The resulting wire-like samples exhibited anisotropic electrical conduction, demonstrating the close relationship between growth conditions, morphology, and charge transport. The study contributes to the broader goal of controlling III-nitride nanostructures for future low-dimensional electronic devices.

Gas sensing is one of the most direct applications of low-dimensional materials because their high surface-to-volume ratios allow adsorbed molecules to influence a substantial fraction of the conductive channel [4]. Nevertheless, pristine materials do not always provide sufficient adsorption strength, selectivity, or response magnitude. Surface modification and structural engineering are therefore important.

Duan et al. demonstrated that site-selective fluorination can markedly improve the ammonia-sensing performance of graphene (contribution 4). Covalent C–F bonds were introduced through an ion-beam-induced process, allowing the fluorination sites to be spatially controlled. Compared with unmodified graphene, the fluorinated material exhibited an eightfold enhancement in its response to ammonia and a limit of detection approaching 65 ppb. This work is a representative example of how targeted chemical functionalization can convert the intrinsically weak adsorption of a two-dimensional surface into an efficient sensing interaction.

Metal oxides remain another important group of gas-sensitive materials. Their performance depends strongly on the crystal phase, defect chemistry, morphology, porosity, and operating temperature. Tian et al. prepared nanosheet-assembled, flower-like γ -Fe₂O₃, α -Fe₂O₃, and mixed-phase α/γ -Fe₂O₃ structures and evaluated their acetone-sensing behavior (contribution 5). The mixed-phase material annealed at 400 °C exhibited superior sensing performance compared with either individual phase. These results highlight the potential of phase-interface engineering, in addition to conventional particle-size and surface-area optimization, for enhancing gas-sensing reactions.

Zhang et al. reported porous, tremella-like NiFe₂O₄ structures assembled from ultrathin nanosheets for the detection of toluene (contribution 6). The sensor achieved a detection limit of 50 ppb and displayed good response and recovery characteristics, reproducibility, and long-term stability. This study confirms that hierarchical porosity and nanoscale thickness can work together to improve adsorption, reaction kinetics, and electrical transduction.

Although highly responsive materials are essential, practical gas analysis often requires the discrimination of several gases or complex mixtures. A single sensing element may not provide sufficient selectivity, especially under fluctuating temperature and humidity. Wang et al. reviewed advanced algorithms for electronic noses based on low-dimensional

metal oxides (contribution 7). This article discusses classical pattern-recognition approaches, including support vector machines, as well as more recent neural-network architectures such as convolutional and recurrent neural networks. Classical algorithms can perform well when appropriate features are selected and the number of gas categories is limited. However, deep-learning approaches offer greater potential for processing complex, time-dependent, and mixed-gas signals. The review also emphasizes sensor drift as a persistent challenge. This contribution illustrates the transition from material-centered sensing toward the co-design of sensing arrays, data processing, feature extraction, and intelligent decision-making.

Promising low-dimensional materials cannot be translated into practical electronics unless reliable transfer, patterning, contact formation, and large-area processing methods are available. The weak van der Waals adhesion and atomic-scale thickness of two-dimensional layers make them particularly vulnerable to contamination, mechanical damage, thermal exposure, and chemical attack during fabrication.

Ghiami et al. examined layer-transfer and photolithography processes for integrating two-dimensional transition-metal dichalcogenides into electronic devices (contribution 8). A dry-transfer method based on thermal-release tape was compared with a wet-transfer process involving a potassium hydroxide solution. The dry-transfer approach better preserved the quality of the two-dimensional layers. This contribution addresses one of the most important gaps between the synthesis of low-dimensional materials and their scalable implementation in device technologies.

Low-dimensional materials also offer new possibilities beyond conventional sensing and logic. Huang et al. reviewed transistor-based synaptic devices for neuromorphic computing (contribution 9). Silicon nanomembranes, carbon nanotubes, nanoscale metal oxides, and two-dimensional materials have all been employed to emulate biological synaptic behavior. The review classifies these devices according to their operating principles and summarizes their fabrication processes and synaptic characteristics. Although significant progress has been made in reproducing functions, practical neuromorphic systems still require improved device uniformity, endurance, retention, linearity, energy efficiency, and array-level integration.

Low-dimensional and porous crystalline materials are also being developed for the detection of hazardous substances in water and other complex environments. These applications require not only high sensitivity but also chemical selectivity, stability in liquids, resistance to fouling, and reliable operation in multi-component samples.

Sayed et al. theoretically investigated one-dimensional fluidic phononic crystal sensors composed of different quasi-periodic sequences (contribution 10). A defect layer containing a lead nitrate solution produced a resonant mode whose frequency shifted with analyte concentration. Fibonacci, Octonacci, Thue–Morse, and double-period arrangements were compared. Among the investigated configurations, the double-period structure provided the best calculated performance, including a high sensitivity and quality factor. This study expands the scope of low-dimensional sensing beyond electronic or chemical-resistive mechanisms and shows that engineered acoustic-wave propagation can be used to detect hazardous dissolved substances.

Kustov et al. reviewed the use of porous coordination polymers, including metal–organic frameworks and covalent organic frameworks, in sensors for toxicants (contribution 11). Their discussion covers electrochemical and photoluminescent sensing, as well as the use of porous frameworks as pre-concentrators. The review demonstrates the broad applicability of porous crystalline materials while also drawing attention to the need for hydrolytic stability, selective recognition in complex media, and the reproducible preparation of framework-based composites and devices.

The impact of low-dimensional materials extends beyond direct sensing. Their high electrical conductivity, large surface area, mechanical strength, and tunable interfaces also make them useful in energy conversion and storage. Du et al. reviewed graphene-based composites for lithium-ion batteries, sodium-ion batteries, potassium-ion batteries, aluminum-ion batteries, and supercapacitors (contribution 12). Graphene can provide conductive networks, shorten ion-transport pathways, buffer volume changes, and improve the mechanical integrity of active electrode materials. At the same time, restacking, limited accessible surface area, interfacial instability, and manufacturing cost continue to restrict practical performance. Although this contribution focuses on energy storage, it reinforces several principles relevant to low-dimensional electronics and sensing, particularly the importance of composite design, interface control, and scalable processing.

In conclusion, this Special Issue provides a broad view of low-dimensional electronics and sensing, ranging from first-principles calculations and controlled crystal growth to surface functionalization, gas sensing, phononic structures, device fabrication, intelligent recognition, neuromorphic computing, and energy storage. The contributions collectively show that progress in this field is driven not only by discovering new materials but also by understanding and controlling their surfaces, interfaces, fabrication processes, and interactions with data-processing systems. Continued interdisciplinary collaboration among materials science, chemistry, physics, electrical engineering, microfabrication, and computer science will be essential for transforming these advances into reliable and practical technologies.

Conflicts of Interest: The authors declare no conflicts of interest.

List of Contributions

1. Huang, S.; Jiao, M.; Wang, X.; He, X. A First-Principles Study on the Structural and Carrier Transport Properties of Inorganic Perovskite CsPbI₃ under Pressure. *Crystals* **2022**, *12*, 648. <https://doi.org/10.3390/cryst12050648>.
2. Zhao, M.; Hao, Y.; Zhang, C.; Zhai, R.; Liu, B.; Liu, W.; Wang, C.; Jafri, S.H.M.; Razaq, A.; Papadakis, R.; et al. Advances in Two-Dimensional Materials for Optoelectronics Applications. *Crystals* **2022**, *12*, 1087. <https://doi.org/10.3390/cryst12081087>.
3. Muthuraj, V.R.; Liu, W.; Collins, H.; Li, W.; Hamwey, R.; DenBaars, S.P.; Mishra, U.K.; Keller, S. N-Polar Indium Nitride Quantum Dashes and Quantum Wire-like Structures: MOCVD Growth and Characterization. *Crystals* **2023**, *13*, 699. <https://doi.org/10.3390/cryst13040699>.
4. Duan, T.; Li, H.; Daukiya, L.; Simon, L.; Leifer, K. Enhanced Ammonia Gas Adsorption through Site-Selective Fluorination of Graphene. *Crystals* **2022**, *12*, 1117. <https://doi.org/10.3390/cryst12081117>.
5. Tian, R.; Tan, H.; Chen, G.; Guan, H.; Dong, C.; Yin, Z. Novel Mixed-Phase α/γ -Fe₂O₃ Micro-Flower Assembled with Nanosheets for Enhancing Acetone Detection. *Crystals* **2023**, *13*, 810. <https://doi.org/10.3390/cryst13050810>.
6. Zhang, Y.; Qu, H.; Gang, C.; Guan, H.; Dong, C.; Yin, Z. Porous, Tremella-like NiFe₂O₄ with Ultrathin Nanosheets for ppb-Level Toluene Detection. *Crystals* **2023**, *13*, 865. <https://doi.org/10.3390/cryst13060865>.
7. Wang, X.; Zhou, Y.; Zhao, Z.; Feng, X.; Wang, Z.; Jiao, M. Advanced Algorithms for Low Dimensional Metal Oxides-Based Electronic Nose Application: A Review. *Crystals* **2023**, *13*, 615. <https://doi.org/10.3390/cryst13040615>.
8. Ghiami, A.; Sun, T.; Fiadziushkin, H.; Tang, S.; Grundmann, A.; Heuken, M.; Kalisch, H.; Vescan, A. Optimization of Layer Transfer and Photolithography for Device Integration of 2D-TMDC. *Crystals* **2023**, *13*, 1474. <https://doi.org/10.3390/cryst13101474>.
9. Huang, W.; Zhang, H.; Lin, Z.; Hang, P.; Li, X. Transistor-Based Synaptic Devices for Neuromorphic Computing. *Crystals* **2024**, *14*, 69. <https://doi.org/10.3390/cryst14010069>.
10. Sayed, A.G.; Hajjiah, A.; Tlija, M.; Bellucci, S.; Abukhadra, M.R.; Elsayed, H.A.; Mehaney, A. Enhanced Performance of Fluidic Phononic Crystal Sensors Using Different Quasi-Periodic Crystals. *Crystals* **2024**, *14*, 925. <https://doi.org/10.3390/cryst14110925>.

11. Kustov, L.; Vergun, V.; Zakharov, V.; Aslanov, L. Metal–Organic Frameworks as Materials for Applications in Sensors for Toxicants. *Crystals* **2026**, *16*, 279. <https://doi.org/10.3390/cryst16050279>.
12. Du, Y.; Wang, M.; Ye, X.; Liu, B.; Han, L.; Jafri, S.H.M.; Liu, W.; Zheng, X.; Ning, Y.; Li, H. Advances in the Field of Graphene-Based Composites for Energy–Storage Applications. *Crystals* **2023**, *13*, 912. <https://doi.org/10.3390/cryst13060912>.

References

1. Korotcenkov, G. Current Trends in Nanomaterials for Metal Oxide-Based Conductometric Gas Sensors: Advantages and Limitations. Part 1: 1D and 2D Nanostructures. *Nanomaterials* **2020**, *10*, 1392. [[CrossRef](#)] [[PubMed](#)]
2. Baig, N. Two-Dimensional Nanomaterials: A Critical Review of Recent Progress, Properties, Applications, and Future Directions. *Compos. Part A Appl. Sci. Manuf.* **2023**, *165*, 107362. [[CrossRef](#)]
3. Luo, Y.; Abidian, M.R.; Ahn, J.-H.; Akinwande, D.; Andrews, A.M.; Antonietti, M.; Bao, Z.; Berggren, M.; Berkey, C.A.; Bettinger, C.J.; et al. Technology Roadmap for Flexible Sensors. *ACS Nano* **2023**, *17*, 5211–5295. [[CrossRef](#)] [[PubMed](#)]
4. Tyagi, D.; Wang, H.; Huang, W.; Hu, L.; Tang, Y.; Guo, Z.; Ouyang, Z.; Zhang, H. Recent Advances in Two-Dimensional-Material-Based Sensing Technology toward Health and Environmental Monitoring Applications. *Nanoscale* **2020**, *12*, 3535–3559. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.