

Interface and Integration Challenges in 0D/2D Hybrid Photodetection: Optimizing Assembly, Interface and Charge Transfer

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This review article examines how combining nanoscale particles with atomically thin semiconductors can improve light-detection technologies. It emphasizes that performance depends largely on how these materials are connected, rather than on the materials themselves. By analyzing fabrication methods and interface design, the authors identify key factors that control efficiency, speed, and stability, and outline practical guidelines for developing more reliable photodetectors for imaging, sensing, and communication

Modern optoelectronic technologies rely heavily on photodetectors that can respond quickly, detect weak signals, and operate across a wide range of wavelengths. These devices are essential for applications such as imaging, environmental monitoring, optical communication, and wearable electronics. However, conventional semiconductor materials are reaching their limits when it comes to balancing light absorption, charge transport, and large-scale integration. This has led researchers to look for new material systems that can overcome these trade-offs. In recent years, low-dimensional materials have drawn strong interest. Zero-dimensional (0D) nanomaterials, such as quantum dots, are excellent light absorbers and can be tuned to respond to different wavelengths simply by changing their size. On the other hand, two-dimensional (2D) semiconductors offer very thin, high-quality pathways for charge transport, along with good control through external fields. Because of these complementary strengths, combining 0D and 2D materials has become a promising strategy for improving photodetector performance. However, even with many reported studies, device performance still varies widely, and it is often not clear why similar systems behave differently. One important reason for this inconsistency is the role of the interface between the two materials. At this junction, key processes such as charge transfer, recombination, and carrier trapping take place. Small differences in how the materials are connected—such as surface chemistry, defects, or structural alignment—can strongly affect how well a device performs. Despite its importance, the interface is often treated differently from study to study, and the overall understanding remains somewhat scattered.

This review is motivated by the need to bring together these different pieces of work and look at them in a more organized way. Rather than presenting new experimental results, the goal is to step back and examine how previous studies connect to each other, especially in terms of how

fabrication methods and interface properties influence device behavior. By putting these results side by side, it becomes easier to see common patterns and identify what really matters for performance. The value of this approach is that it can help clarify where the main challenges lie. Issues such as device variability, long-term stability, and difficulty in scaling up fabrication are repeatedly reported, but not always discussed in a unified way. By focusing on the interface as a central factor, this review aims to highlight practical directions for improving device reliability and consistency. In the end, the purpose of this work is to provide a clearer picture of the field and to suggest how future research can move forward more systematically. A better understanding of interface effects is expected to play a key role in developing photodetectors that are not only high performing, but also stable and scalable enough for real-world applications.

The research group of Prof. Jeongyong Kim from Sungkyunkwan University reviews recent progress in hybrid photodetectors that combine zero-dimensional (0D) nanomaterials with two-dimensional (2D) semiconductors, with a particular focus on how interfaces determine device performance. The article brings together a wide range of studies to explain how these hybrid systems work and why their performance can vary so much depending on how they are fabricated.

The review first introduces the basic idea behind 0D/2D hybrid photodetectors. In these systems, 0D nanomaterials such as quantum dots act as efficient light absorbers, while 2D semiconductors serve as fast pathways for charge transport. This combination allows devices to achieve higher sensitivity and detect a broader range of wavelengths than conventional photodetectors. The authors explain that this improvement mainly comes from how light-generated charges are separated and transferred at the interface between the two materials.

A major part of the review focuses on fabrication methods and how they influence the quality of the interface. Two main approaches are discussed: solution-based processes, such as spin coating and printing, and in-situ growth methods, where nanomaterials are formed directly on the 2D surface. Each method has its advantages and limitations. For example, solution processes are simple and scalable but often leave insulating organic layers that hinder charge transfer, while in-situ growth can produce better contact but is more difficult to control. By comparing these approaches, the authors show how fabrication choices directly affect device performance.

The review then discusses key interface-related factors that govern device operation. These include band alignment between materials, which determines how easily charges move across the interface, as well as surface chemistry and defect states that can trap charges. The authors explain that these factors control important characteristics such as sensitivity, response speed, and noise. Different charge and energy transfer mechanisms, including direct charge transfer and non-radiative energy transfer, are also described to help clarify how signals are generated and amplified in these devices.

Another important topic covered in the review is the trade-off between high sensitivity and fast

response. Many high-performance devices rely on charge trapping to amplify signals, but this often slows down the response time. The authors highlight how careful interface engineering can help balance these competing effects. In addition, the review examines stability issues, noting that interfaces can degrade over time due to environmental exposure or changes in surface chemistry, which can affect long-term device performance.

Finally, the article summarizes representative device performances reported in the literature and discusses common challenges such as variability between devices and difficulties in scaling up fabrication. By organizing these results in a systematic way, the review provides a clearer picture of the field and identifies key directions for future improvement.

Overall, this work offers a comprehensive overview of how interface design plays a central role in 0D/2D hybrid photodetectors and provides practical insights for developing more reliable and high-performance optoelectronic devices

Further progress in 0D/2D hybrid photodetectors will depend on improving control over interfaces and ensuring consistent device performance. Achieving uniform, defect-controlled interfaces across large areas remains a key challenge for practical applications. Advances in surface chemistry, ligand design, and scalable fabrication methods are expected to play an important role. In addition, combining experimental work with computational approaches may help identify better material combinations more efficiently. Improving long-term stability under real operating conditions is also essential. With continued efforts in these directions, 0D/2D hybrid systems are likely to move closer to practical use in imaging, sensing, and communication technologies.

Keywords: interface engineering, charge transfer, photodetectors, ligand exchange, band alignment, trap states

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The research group led by Prof. Jeongyong Kim at the Department of Energy Science, Sungkyunkwan University is dedicated to advancing low-dimensional nanomaterials for optoelectronic and energy-conversion applications. The group's research is organized into areas such as: (i) colloidal synthesis of quantum-confined nanocrystals with precise control over size, composition (ii) fabrication and characterization of 2D semiconductor devices, such as photodetectors based on transition metal dichalcogenides (MoS₂, WS₂, WSe₂) and (iii) Optical characterization of mixed-dimensional hybrid systems (0D/2D and 1D/2D) with confocal microscopy systems. The group has published peer-reviewed articles in leading journals, including Nature Communications, ACS Nano, Advanced Materials, and Nano Letters, and has many graduated students whose careers span academia and industry worldwide.

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