

Miniaturized ultraviolet spectral imaging with GaN photodiode arrays

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Spectral imaging is increasingly important in science and technology. Going beyond conventional RGB imaging, it captures both spatial and spectral information, providing distinctive light fingerprints that can uncover the composition, properties, and dynamics of materials through light–matter interactions. This capability is valuable in a wide range of fields, including food safety, medical diagnostics, and agricultural monitoring.¹ However, current spectral imaging systems remain bulky and complex because traditional spectrometers typically depend on gratings or interferometers, often with moving parts, which makes miniaturization difficult.^{2–5} At the same time, the demand and potential applications for miniaturized spectral imaging are rapidly growing, yet these instrumental limitations continue to restrict their broader applications. As a result, spectral imaging is still mostly limited to laboratory or large-scale setups. This gap has fueled strong interest in the development of miniaturized spectrometers that can bring spectral imaging into portable and chip-scale platforms.^{2–4}

Over the past decade, there has been significant progress in miniaturized spectrometers. Approaches based on dispersive nanostructures^{6,7} and filters⁸ (including quantum-dot-based filters⁹), bandgap-graded nanowires,¹⁰ and tunable heterostructures (including two-dimensional materials,^{11–15} organic materials,¹⁶ and III–V semiconductors-based junctions¹⁷) have demonstrated compact device designs and effective computational reconstruction methods.⁴ However, extending these technologies into the ultraviolet (UV) spectral range, a spectral region crucial for chemical sensing and environmental monitoring, remains a major challenge. To address this, Yu and colleagues¹⁸ now report a photodiode array spectral imager that successfully pushes the miniaturized spectrometer field into this previously inaccessible spectral regime.

At the core of this result is a simple yet powerful idea: stacking two photodiodes in a vertical n–p–n configuration to create a “cascaded photodiode,”¹⁸ a multilayer heterostructure. One photodiode is made from AlGaIn and the other from GaN. By adjusting the bias voltage, the device can selectively activate the lower photodiode, the upper photodiode, or both, producing bias-dependent responsivities that change with wavelength. Recording the photocurrent under different bias voltages builds a rich response matrix, which is then decoded using machine learning algorithms to reconstruct the unknown incident spectrum. The authors further demonstrate this concept by fabricating photodiode arrays on a sapphire wafer [Fig. 1(a)]. Each pixel measures $300\ \mu\text{m} \times 300\ \mu\text{m}$, and a 10×10 array serves as a compact imager capable of capturing both spectral and spatial information simultaneously. The device operates across a wavelength range of ~ 250 to $365\ \text{nm}$, reaching into the UV for the first time in a miniaturized on-chip format. Its performance is impressive, with a peak wavelength accuracy of $\sim 0.6\ \text{nm}$, a resolution of spectral features separated by $\sim 5\ \text{nm}$, and a fast temporal response of less than $10\ \text{ns}$.

The internationally collaborating team also showcased application capability by detecting thin films of various organic materials placed side by side on a substrate.¹⁸ In the measurements, the imager generated a three-dimensional data cube [Fig. 1(b)] that revealed both the spatial position of each film and its distinct spectral signature. In essence, the photodiode array delivers what various application fields have long been seeking: compact, fast, and accurate spectral imaging for sensing without moving parts.

In contrast to earlier demonstrations,^{6,9–15} scaling from proof-of-concept devices to practical imaging arrays has remained a major challenge. The team addressed this obstacle by turning to one of the most established building blocks in optoelectronics: the conventional semiconductor photodiode.^{17,18} This choice grounds their design in a technology with decades of industrial development, robust fabrication methods, and proven reliability. Most importantly, the array demonstration confirms that the approach is not limited to a single pixel but can be scaled to many detectors working in parallel. The integration of algorithms further enhances the spectral reconstruction process. This combination of mature hardware with modern computational tools reflects a broader trend in photonics: algorithmically assisted devices that overcome the inherent limits of their physical design and hardware fabrication.^{2–4}

Access to the UV spectral range is especially important because many molecules have strong absorption features below $300\ \text{nm}$. This makes it highly useful for identifying chemical compounds and studying biomolecular structures. A miniaturized imager operating in this range could have a broad impact—from improving food and environmental safety through rapid contaminant detection¹ to enabling label-free analysis and portable diagnostics in medicine and to supporting space exploration where lightweight instruments are essential for planetary missions, among other applications [Fig. 1(c)].

Equally important is the device’s temporal performance. With response times of $< 10\ \text{ns}$, the cascaded photodiodes are orders of magnitude faster than most other miniaturized spectrometers. Such fast response speed can enable real-time spectral imaging in dynamic environments, such as following chemical reactions, monitoring combustion, or capturing short-lived biological events. Combined with array-level integration, this speed points toward the possibility of spectral imaging beyond video-rate, a capability that traditional benchtop systems struggle to deliver.⁸ With its compact size, UV coverage, and fast response speed, the cascaded photodiode array sets a new benchmark for portable spectroscopy, showing how rethinking device design can surpass bulkier predecessors.

As with any breakthrough, the path forward presents both opportunities and challenges. A key direction is broadening the operational bandwidth: by tailoring the semiconductor composition, for example, with indium-rich alloys, the photodiode concept could evolve into a universal spectrometer-on-a-chip spanning from the UV to infrared spectral range. Improving resolution and array size is another important goal. Although the current pixels measure hundreds of micrometers, advancing toward micrometer-scale dimensions, inspired by micro-light emitting diode fabrication, could enhance spatial resolution and reduce chip size, whereas larger arrays would increase the field of view

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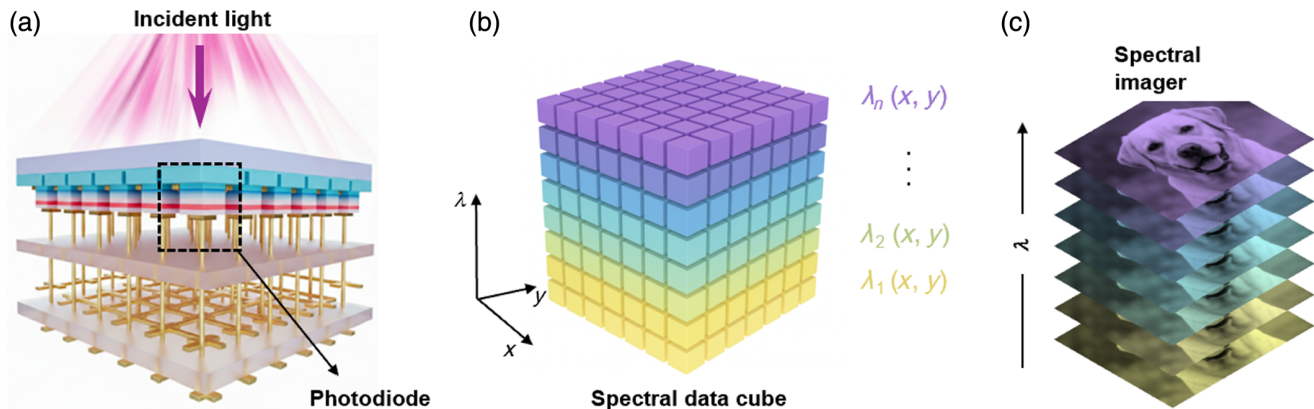


Fig. 1 Miniaturized UV spectral imager with a photodiode array. (a) Schematic illustration of a spectral imager array chip. (b) Each pixel within the spectral imager array records wavelength (λ)-dependent photocurrent signals for reconstructing a three-dimensional spectral data cube [$\lambda_n(x, y)$]. (c) Potential spectral imaging application example. Picture courtesy of Prof. Haiding Sun.

for more complex imaging tasks. On the computational side, efficient algorithms will be essential for portable applications, requiring neural networks optimized for real-time, low-power operation on dedicated processors. Finally, manufacturability at scale remains a critical hurdle: although GaN and AlGaIn technologies are well established, achieving uniform epitaxy and consistent performance across large wafers, together with ensuring long-term stability, will be important for practical applications.

Just as digital cameras transformed the way we capture images, compact spectral imagers of this kind could once again change the way we see the world. This work demonstrates how thoughtful heterostructure device design,¹¹ built on mature technologies and enhanced by modern algorithms, can overcome long-standing barriers. Looking ahead, miniaturized spectrometers and their arrays may form the foundation of next-generation portable spectroscopy, reshaping research, industry, and everyday life.

References

1. L. Smeesters et al., "2025 photonics for agrifood roadmap: towards a sustainable and healthier planet," *J. Phys.: Photonics* **7**, 032501 (2025).
2. Z. Yang et al., "Miniaturization of optical spectrometers," *Science* **371**, eabe0722 (2021).
3. W. Cai et al., "Simple yet powerful," *Nat. Photonics* **18**, 651–653 (2024).
4. Y. Zhang et al., "Reconstructive spectrometers: hardware miniaturization and computational reconstruction," *eLight* **5**, 23 (2025).
5. S. Yuan et al., "Geometric deep optical sensing," *Science* **379**, eade1220 (2023).
6. F. Tang et al., "Metasurface spectrometers beyond resolution-sensitivity constraints," *Sci. Adv.* **10**, eadr7155 (2024).
7. B. Redding et al., "Compact spectrometer based on a disordered photonic chip," *Nat. Photonics* **7**, 746–751 (2013).
8. M. Yako et al., "Video-rate hyperspectral camera based on a CMOS-compatible random array of Fabry–Pérot filters," *Nat. Photonics* **17**, 218–223 (2023).
9. J. Bao and M. G. Bawendi, "A colloidal quantum dot spectrometer," *Nature* **523**, 67–70 (2015).
10. Z. Yang et al., "Single-nanowire spectrometers," *Science* **365**, 1017–1020 (2019).
11. H. H. Yoon et al., "Miniaturized spectrometers with a tunable van der Waals junction," *Science* **378**, 296–299 (2022).
12. M. G. Uddin et al., "Broadband miniaturized spectrometers with a van der Waals tunnel diode," *Nat. Commun.* **15**, 571 (2024).
13. X. Cui et al., "Miniaturized spectral sensing with a tunable optoelectronic interface," *Sci. Adv.* **11**, eado6886 (2025).
14. C. Ma et al., "Intelligent infrared sensing enabled by tunable moiré quantum geometry," *Nature* **604**, 266–272 (2022).
15. W. Deng et al., "Electrically tunable two-dimensional heterojunctions for miniaturized near-infrared spectrometers," *Nat. Commun.* **13**, 4627 (2022).
16. X. He et al., "A microsized optical spectrometer based on an organic photodetector with an electrically tunable spectral response," *Nat. Electron.* **7**, 694–704 (2024).
17. J. Wang et al., "Single-pixel p-graded-n junction spectrometers," *Nat. Commun.* **15**, 1773 (2024).
18. H. Yu et al., "A miniaturized cascaded-diode-array spectral imager," *Nat. Photonics* (2025).