2-5-16. Photodetectors

Overview

Photodetectors have evolved into a foundational technology for measuring and controlling a wide variety of optical signals, beginning with the discovery of the photoelectric effect in the 19th century and progressing through the advent of vacuum tubes, semiconductors, and superconducting devices. In recent years, the emergence of novel functional materials, such as quantum dots, two-dimensional materials, organic thin films, organic-inorganic hybrid materials, and perovskites, has enabled highly sensitive detection of not only visible light but also near-infrared and polarized light.

Current Status and Frontiers

Advances in photodetector technology have been driven by continual innovation in materials and device architecture. Early devices included photomultiplier tubes (PMTs), semiconductor photodetectors (such as Si and InGaAs), and avalanche photodiodes (APDs), with steady progress made in quantum efficiency, sensitivity, noise reduction, and response speed. The development of superconducting detectors (such as SSPDs and transition-edge sensors) has recently advanced at a remarkable rate—enabling single-photon-level detection through the application of high bias voltages (hundreds of volts or more) and operation at ultralow temperatures (< 2 K).

Traditional photodetectors are primarily sensitive to photon quantity (intensity), and do not directly measure wavelength or polarization information. Therefore, optical components such as diffraction gratings or polarizers are required for spatial separation and measurement of wavelength or polarization. In contrast, leveraging the wavelength-selective absorption properties of organic molecules, organic photodetectors can simultaneously achieve photon counting and color separation, making color filters unnecessary. For example, a multilayer organic CMOS sensor, with each layer responsive to blue, green, or red light, can independently read out signals for each color from a single device, improving both light utilization and pixel aperture ratio. Extensive research is underway toward practical implementation. Recently, vertically-stacked image sensors using halide perovskites with tunable bandgaps, instead of organic materials, have also been reported.

Organic thin film-based photoelectric conversion devices have exhibited photomultiplication (current gain) comparable to that of PMTs. This phenomenon, first reported by Hiramoto et al. in 1994, results from electric field concentration induced by carrier trapping at the organic layer/electrode interface, giving rise to tunneling current. Furthermore, Ishii et al. have achieved amplification and detection of extremely weak light (as faint as moonlight) more than 1000-fold at operating voltages below 1 V, by exploiting a unique interface between inorganic semiconductors and metal complexes. For instance, when weak light is irradiated onto a thin film where perovskite nanoparticles and Eu complexes are immobilized on a porous titanium oxide membrane, photogenerated carriers in the perovskite are trapped at the Eu complex interface, inducing a strong electric field and significantly amplifying the photoconversion current.

The amplification factor reaches 2,900× at 0.5 V, and even very weak visible light (less than 1/100 sunlight) can be amplified more than 1,000-fold. The sensitivity and noise levels in these devices rival those of amplification-type (e.g., Si or GaAs) photodetectors that require much higher voltages.

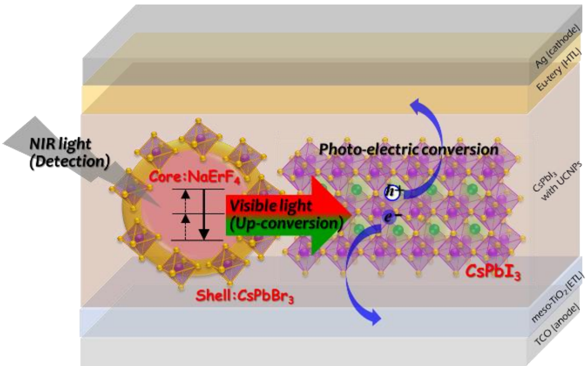

Figure 1. Perovskite-based NIR photodetectors using UC nanoparticles.

Photo- and short-wave infrared (NIR/SWIR) photodetectors hold promises for security, optical communications, and biomedical imaging. Most practical NIR devices currently use InGaAs, with absorption in the 900–1,700 nm range. However, due to the small bandgap, they suffer from substantial dark current (noise), limiting sensitivity compared to Si devices for visible light. Devices using semiconductor quantum dots and organic dyes sensitive to the NIR are actively being developed, but still face challenges relating to toxicity and stability. More recently, upconversion (UC) materials that convert NIR light to visible light have been introduced as a new sensing method. For example, hybrid photoconversion devices combining rare-earth UC particles and $CsPbI_3$ thin films can detect NIR by converting it to visible UC emission, which is then detected by the perovskite film (Fig. 1). While response speed has room for improvement, conversion efficiencies as high as 75% have been achieved under low-intensity solar light.

References

1. H. Seo, S. Aihara, T. Watabe, H. Ohtake, T. Sakai, M. Kubota, N. Egami, T. Hiramatsu, T. Matsuda, M. Furuta and T. Hirao, *Jpn. J. Appl. Phys.*, **50**, 024103 (2011).
2. S. Tsarev, D. Proniakova, X. Liu, E. Wu, G. J. Matt, K. Sakhatskyi, L. L. A. Ferraresi, R. Kothandaraman, F. Fu, I. Shorubalko, S. Yakunin, M. V. Kovalenko, *Nature*, **642**, 592 (2025).
3. T. Katsume, M. Hiramoto, M. Yokoyama, *Appl. Phys. Lett.* **64**, 2546–2548 (1994).
4. A. Ishii, A. K. Jena, T. Miyasaka, *J. Phys. Chem. Lett.*, **10**, 5935–5942 (2019).
5. A. Ishii, T. Miyasaka, *Adv. Photon. Res.*, **4**, 2200222 (2023).

Future Perspectives and Directions

The detection of various types of optical information, spanning sensor architecture, optics, electronics, and signal processing, continues to see dramatic advances. At its core, the photodetector utilizes the fundamental material property of “light absorption.” The development of new materials and devices capable of highly precise detection and utilization of various optical information is expected to form the core foundation technology for next-generation photonics, including quantum communications, biomedical imaging, and astronomical observation (For circularly polarized light detection, see the section on inorganic chiral materials).

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