Progress and Prospects of Topological Materials in Photodetection

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Abstract: Topological materials exhibit unique electronic properties, making them promising for photodetection. This paper presents a comprehensive review of the emerging applications of topological materials in photodetection, focusing on their exceptional electronic properties that enable superior device performance. The article briefly explains the transport mechanisms of topological insulators, topological semimetals, topological superconductors, as well as new types of topological materials such as chiral topological materials and ferroelectric topological materials.The article also systematically examines recent breakthroughs demonstrating how these materials achieve remarkable photodetection capabilities through enhanced responsivity, improved detectivity, and ultrafast response times. The paper discusses promising implementation scenarios across multiple technological domains, particularly in high-speed optical communications, advanced infrared imaging systems, and next-generation quantum devices. Although challenges persist in material synthesis and device integration, topological photodetectors represent a transformative advancement in optoelectronics, offering unprecedented combinations of broadband sensitivity, rapid response, and robust performance that could redefine detection technologies across scientific and industrial applications.

1 INTRODUCTION

Photodetectors have significant applications in various fields such as optical communication, imaging, security monitoring, and biosensing (Liang et al., 2018). Research indicates that topological materials can detect in the range from infrared to terahertz waves, breaking through the limitations of traditional detection materials. They also possess high responsivity, response time, and a high signal-to-noise ratio. These properties can be further enhanced through structural designs such as doping, nanowires, and heterojunctions, as well as using strain and other control methods. Moreover, with the increasing discovery of topological materials and the continuous progress in their preparation techniques, the application of topological materials in photoelectric detection will have greater potential.

This article aims to systematically explore the unique advantages, performance regulation methods, device design strategies, and application potential of topological materials in the field of photoelectric detection, providing a research foundation for the development of a new generation of high-performance photoelectric detectors.

2 OVERVIEW OF TOPOLOGICAL MATERIALS

Topological materials exhibit unique electronic properties due to their special surface states. They are mainly classified into four types as topological insulator (TI), topological crystalline insulator (TCI), topological semimetal (TSM), and topological superconductor (TSC).

TIs are bulk insulating but with conductive surface states protected by time reversal symmetry, enabling high carrier mobility.

TCIs have surface states protected by crystal symmetries such as mirror symmetry, as seen in SnTe. They show insulating bulk and conductive edges, suitable for photodetection.

TSMs feature bulk band crossing (Dirac/Weyl points) near the Fermi level, leading to high carrier concentration and mobility. Examples include TaAs

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(Weyl) and Na_3Bi (Dirac), ideal for low-power, high-sensitivity photodetectors.

TSCs host Majorana zero-energy modes on surfaces, with robust, defect-resistant conduction channels. Their combination of superconductivity and topological protection is valuable for energy-efficient devices.

Moreover, some materials cannot be classified within the traditional topological phase framework. These are referred to as new topological phases, including topological chiral crystals and ferroelectric topological materials.

Topological chiral crystals lack mirror symmetry in their lattice structure and display topological behaviors even without symmetry protection. In some cases, they resemble topological semimetals, especially when band crossing points (such as Dirac or Weyl points) appear near the Fermi surface, offering potential for broad-spectrum photodetection.

Topological ferroelectric materials share features of both topological insulators and superconductors, making them highly promising for photoelectric detection applications.

3 PHOTODETECTOR: PRINCIPLES, MANUFACTURING PROCESS, AND STRUCTURES

3.1 Principle

Topological materials demonstrate exceptional photodetection properties owing to their unique band structures, such as surface states and linear dispersion, enabling strong light absorption, particularly in the IR and THz regions. Their high carrier mobility and low scattering rates facilitate rapid charge transport with minimal recombination losses, while topological protection further enhances carrier stability. Moreover, the surface states significantly enhance photocurrent generation, even under low-energy excitation, thereby improving both sensitivity and response speed in photodetectors.

In addition to these mechanisms, studies have shown that doping with magnetic elements can break the time-reversal symmetry of the surface states in topological insulators, thereby inducing a band gap in these states. Consequently, the band gap of topological insulator surface states can be effectively controlled through the introduction of magnetic impurities (Swatek et al., 2020). Studies have also demonstrated that strain can influence the optical absorption of topological insulator films by altering crystal symmetry or modulating the band gap of surface states. Such strain-induced regulation, rather than changes in film thickness, enables precise control at the device level, facilitating efficient photoelectric detection across a broad photon energy range. Furthermore, this approach can enhance the previously reported anisotropic photoelectric current response, offering new opportunities for the development of advanced photodetectors (Brems et al., 2018).

3.2 Manufacturing Process and Structures

Preparation of transport devices using topological materials primarily involves two methods: thin film growth and heterostructure construction. Thin film growth utilizes molecular beam epitaxy (MBE) for high-quality single-crystal films with precise doping control. Chemical vapor deposition (CVD) produces large-area 2D materials but requires a transfer step. Electrochemical deposition and radio frequency magnetron sputtering directly grow films on substrates, avoiding interface contamination. The hydrothermal method is cost-effective for multi-dimensional heterojunctions.

Heterostructure construction relies on van der Waals stacking, where interfaces are formed without chemical bonds via mechanical transfer, and vertical epitaxial growth for direct contact. In situ insertion of passivation layers optimizes Schottky junction performance.

Device design focuses on performance. Back-to-back heterojunctions suppress dark current through dual interfaces, improving the signal-to-noise ratio. Self-powered p-n junctions operate at zero bias using built-in electric fields. Schottky junctions combine passivation layers to enhance response speed (160 ns) and band coverage (up to 10.6 μm). Photochemical cells separate charge carriers via a solid-liquid interface electric field without external bias. Special structures like plasma antenna coupling enhance terahertz absorption, while topological lasers enable room-temperature lasing, and topological photonic crystal modulators support ultra-high-speed signal transmission.

Material preparation is shifting from traditional mechanical exfoliation to in-situ growth methods to reduce interface defects and improve process compatibility. Device design is embracing multi-dimensional heterojunctions and self-powered structures, with a clear trend toward functional integration. Future challenges include achieving large-scale uniform growth techniques, precise control of interface states and defects, and deep integration with existing semiconductor processes (CMOS, photonic integrated circuits).

4 RESEARCH PROGRESS IN RECENT YEARS

4.1 The Application of Topological Insulators in Photodetection

In the field of topological insulators, Wang et al. (2023) combined transition metal dichalcogenide (MoS_2) with a topological insulator (Sb_2Te_3) to create a self-powered broadband photodetector, addressing the severe recombination issue at the interface of traditional 2D material heterojunctions. The device demonstrated record-low dark current (2.4 pA) and high responsivity (>150 mA/W) in the 500-900 nm wavelength range, offering a new solution for low-power optoelectronic integration (Figure 1).

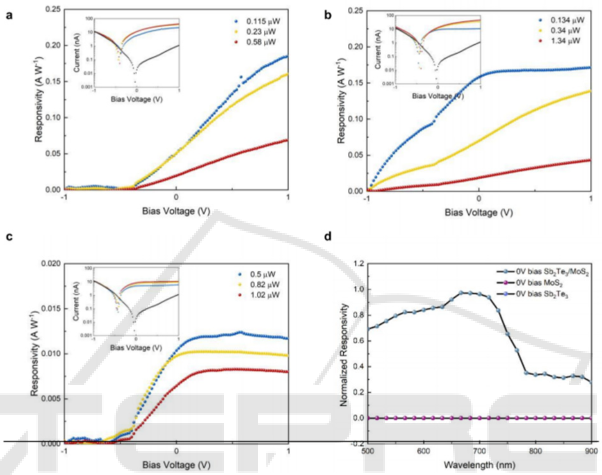

Figure 1: Electrical characterization of Sb2Te3/MoS2 PN junction heterostructure photodetector (Wang et al., 2013)

In the same year, Zhao et al. innovatively proposed a 1D p-Te/2D n-Bi_2Te_3 multidimensional heterojunction structure, fabricated via a hydrothermal method. The device achieved a high on-off ratio (377.45) and excellent stability (only an 18.08% decay over 30 days) in the 365-850 nm wavelength range, filling the technological gap for low-cost, high-performance self-driven photodetectors (Figure 2) (Zhao et al., 2023).

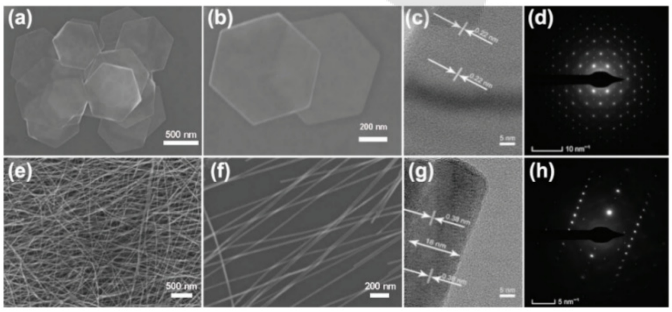

Figure 2: SEM images of Bi2Te3 NSs with different magnifications (Zhao et al., 2023)

In 2024, Ye et al. pioneered the direct electrodeposition of Bi_2Se_3 films on ITO, avoiding interface contamination caused by traditional transfer methods. The resulting photoelectrochemical detector achieved a photocurrent density of 2.87 μA/cm², with significantly improved stability (88% retention after one week), opening a new path for large-scale fabrication of topological insulator films (Ye et al., 2024). In the same year, the Maurya team first combined $TlBiSe_2$ with GaN to construct a vertical heterojunction diode, achieving high-responsivity detection in the ultraviolet to near-infrared (300-900nm) wavelength range. The device exhibited a rectification ratio of 160, overcoming the limitations of traditional broadband detectors that rely on complex band engineering (Figure 3) (Maurya et al., 2024).

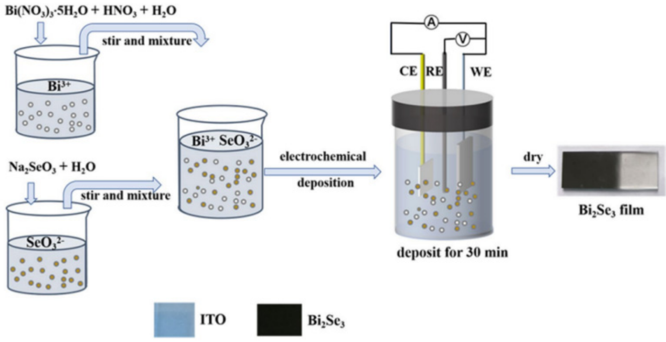

Figure 3: The preparation process of Bi2Se3 film (Ye et al., 2024)

Recent studies on topological insulators have made progress in the design optimization of heterostructure, innovation of fabrication processes, and improvement of device performance. These related research efforts have facilitated breakthroughs in wide-spectrum response, self-powered operation, high sensitivity, and long-term stability of devices, providing new solutions and development paths for achieving high-performance, low-cost, and integrated photodetection technologies.

4.2 The Application of Topological Semimetals in Photodetection

In the field of topological semimetals, Zhang et al. (2022) first designed and fabricated a back-to-back heterojunction photodetector based on the three-dimensional Dirac semimetal $(Cd_{1-x}Zn_x)_3As_2$. The dual-heterojunction structure suppressed the dark current to the picoampere level, achieving a signal-to-noise ratio as high as 10^4. This device simultaneously optimized broadband detection (450 nm–4.5 μm) and ultrafast response (87.5 μs), offering a new architecture for infrared focal plane arrays.

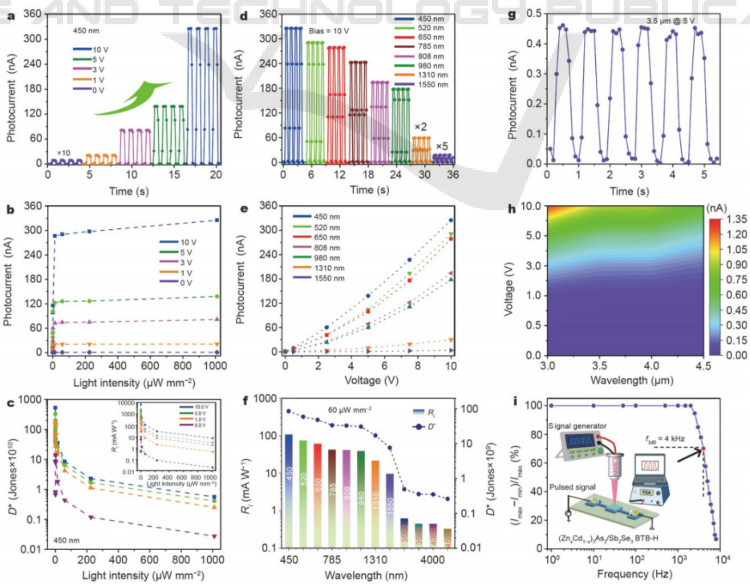

Figure 4: Photodetection performance of the (Cd1-xZnx) As2/Sb2Se3 BTB heterojunction (Zhang et al., 2022)

In 2023, the Lin Wang team innovatively utilized the topological band characteristics of the Dirac semimetal $PtSe_2$, combined with a nanoplasmonic antenna, to achieve high responsivity (0.2 A/W) and picosecond-level response in the terahertz (THz) range (<1.24 meV) at room temperature. This breakthrough surpassed the performance limits of traditional semiconductor materials in low-energy photon detection (Figures 4, 5)(Wang et al., 2022).

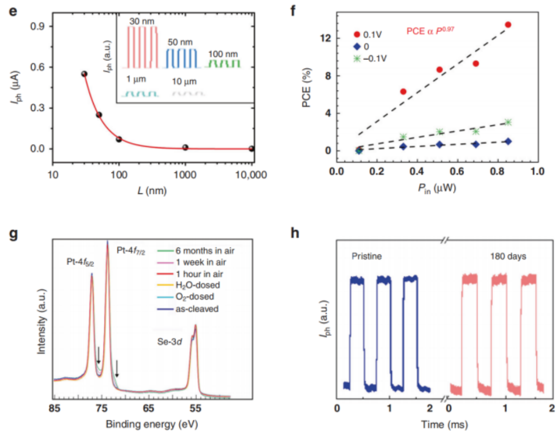

Figure 5: Characteristics of the PtSe2 low-energy photon detector (Wang et al., 2022)

In 2024, Li et al. first observed the strong coupling effect between spin-polarized electrons and phonons in $PtTe_2$ using ultrafast spectroscopy, revealing the microscopic mechanism of anisotropic phonon dynamics. This study laid the theoretical foundation for the application of topological materials in ultrafast optoelectronic devices (Figure 6) (Li et al., 2024).

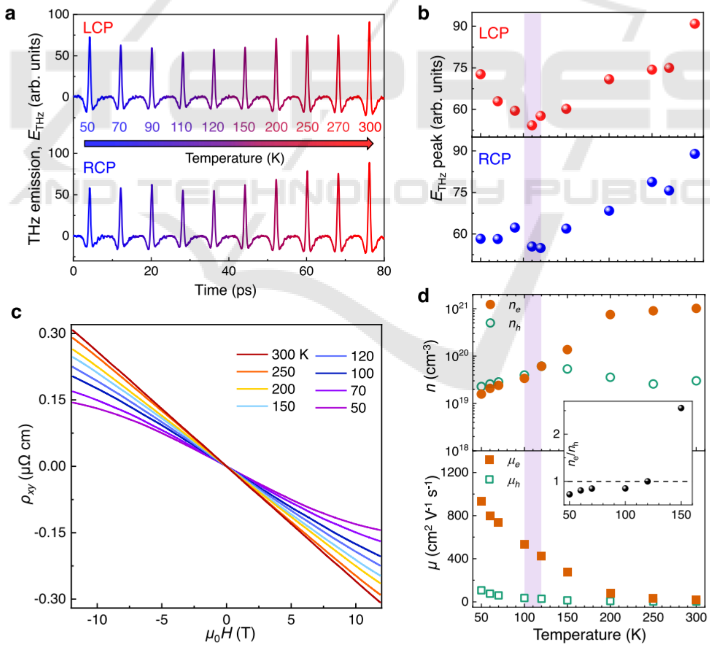

Figure 6: Temperature-dependent THz emission and its correlation with carrier compensation (Li et al., 2024)

Topological semimetals have made significant progress in the field of photoelectric detection, manifested in aspects such as wide-spectrum high response, ultrafast response speed, low dark current, and unique spin-phonon coupling mechanism, providing new material systems and theoretical foundations for the development of high-performance and ultrafast optoelectronic devices.

4.3 The Application of Topological Superconductors in Photodetection

The Pattanayak team (2024) systematically measured the optical constants of $FeTe_{0.6}Se_{0.4}$ topological superconducting nanosheets in the 450-1100 nm range and at 4K-295K. They found that in the superconducting state (4K), the refractive index ranged from 2.81 to 4.26, and the extinction coefficient from 2.24 to 3.21. The material exhibited dual-Drude multi-band characteristics and anomalous dispersion, confirming its high extinction coefficient outperforms traditional copper-based superconductors, providing key parameters for the development of quantum photonic devices like high-temperature superconducting single-photon detectors (Figure 7)(Pattanayak, Rout, & Jha, 2025).

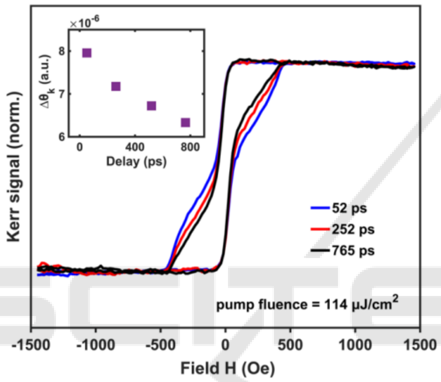

Figure 7: Pump-modulated MOKE loops in the time domain (Pattanayak, Rout, & Jha, 2025).

4.4 The Application of Novel Topological Materials in Photodetection

Topological handedness crystals (such as RhSi and CoSi) and ferroelectric topological materials (such as GeTe and SnTe) demonstrate unique advantages in photoelectric detection. RhSi and CoSi achieve a wide-spectrum response through the quantumized circularly polarized photocurrent effect, and have high sensitivity and fast response characteristics in the terahertz to infrared wavelength range. GeTe and SnTe utilize the synergy of ferroelectricity and topological surface states, showing controllable high photocurrent response rate in the mid-infrared wavelength range. The excellence of these materials stems from their special Berry curvature and band structure, providing important candidate systems for the next generation of high-performance photoelectric detectors.

Research indicates that the photocurrent response of CoSi at 0.4 eV photon energy reaches 550 μA/V², and the responsivity of SnTe at 635 nm wavelength is as high as 49.03 A/W, which is significantly superior to that of traditional semiconductor devices. The efficient working characteristics of these materials under zero bias conditions make them have important application prospects in terahertz sensing and infrared detection fields (Shen et al., 2024).

As seen from the above, research on topological materials has shifted from fundamental property exploration to device applications. Several achievements, such as the first realization of broadband self-powered detection, breakthroughs in terahertz room-temperature detection limits, and the discovery of new mechanisms for light-controlled magnetism, mark the maturity of this field.

5 CONCLUSIONS

Topological materials exhibit unique electronic properties that make them highly suitable for next-generation optoelectronic devices. In optical communication, photodetectors based on topological materials offer ultrafast response times and exceptional carrier mobility, enabling high-speed optical signal detection and transmission for data centers and 5G/6G networks. In infrared imaging and sensing, their broad spectral response, from ultraviolet to terahertz, allows for versatile applications in night vision, thermal imaging, and biomedical sensing. Additionally, in quantum information processing, features such as zero energy gap and chirality enable the realization of quantum bits and support technologies like quantum computing and communication, highlighting their potential in quantum photonic devices.

This review systematically examined five major classes–topological insulators, crystalline insulators, semimetals, superconductors, and novel topological materials–highlighting their distinct mechanisms for enhancing photodetector performance. Key advantages such as ultrafast response, high sensitivity, and low-energy consumption position these materials as superior alternatives to conventional semiconductors.

While significant progress has been made in understanding these materials and developing device architectures like heterojunctions, challenges in large-scale synthesis and device integration remain. Future efforts should focus on optimizing fabrication techniques, improving material quality, and exploring hybrid systems to overcome current limitations. With continued research, topological photodetectors could enable breakthroughs in high-speed optical communication, infrared imaging, and quantum information processing. Their unique combination of robustness and performance promises to drive innovation in next-generation optoelectronic devices, paving the way for transformative applications across scientific and industrial fields.

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