Interface Engineering and Photodetection Performance in CdTe Heterojunction Devices

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Abstract: Cadmium telluride (CdTe) heterojunction photodetectors have emerged as highly promising optoelectronic devices due to their excellent optoelectronic properties, high absorption coefficient in the visible spectrum, and compatibility with large-area fabrication. This review summarizes the fundamental principles, material properties, device architectures, fabrication techniques, performance characteristics, and recent advances in CdTe-based heterojunction photodetectors. Challenges such as interface defects, dark current suppression, and spectral response tailoring are discussed, along with future research directions aimed at enhancing device performance for applications in imaging, sensing, and communication.

Keywords: Heterojunction, photodetectors, Band Diagram, Photoresponse and Time Response.

I. INTRODUCTION

Photodetectors are key optoelectronic components that convert incident photons into electrical signals and form the backbone of numerous modern technologies, including optical communication systems, digital imaging, environmental sensing, security surveillance, and biomedical diagnostics. The rapid growth of these application areas has created a strong demand for photodetectors that offer high sensitivity, fast response, low noise, and long-term operational stability. Achieving these performance metrics depends critically on the choice of semiconductor material and device architecture. Among the various semiconductor materials investigated for photodetection, cadmium telluride (CdTe) has attracted considerable attention due to its highly favorable optoelectronic properties. CdTe is a II–VI compound semiconductor with a direct bandgap of approximately 1.45 eV at room temperature, which closely matches the visible region of the solar spectrum. This near-ideal bandgap enables efficient photon absorption and high quantum efficiency for visible-light detection. In addition, CdTe exhibits a very high absorption coefficient (exceeding 10^4 cm^{-1}), allowing the use of relatively thin absorber layers to capture most of the incident light. This property is particularly advantageous for thin-film photodetectors, where reduced material thickness leads to lower fabrication costs and improved carrier collection efficiency. Furthermore, CdTe benefits from well-established thin-film growth techniques such as close-space sublimation, chemical bath deposition, sputtering, and vapor-phase methods, making it compatible with large-area and scalable device fabrication. To further enhance device performance, CdTe is commonly integrated into heterojunction architectures rather than being used as a standalone absorber. CdTe heterojunction photodetectors are formed by coupling a CdTe absorber layer with a suitable window or contact layer, typically an n-type semiconductor such as CdS, ZnO, ZnSe, or CdSe [1]. The formation of a heterojunction introduces a built-in electric field at the interface due to band alignment and carrier concentration differences between the two materials. This internal electric field plays a crucial role in efficiently separating and transporting photogenerated electron–hole pairs, thereby reducing recombination losses and enhancing photocurrent generation. In addition to improved charge separation, heterojunction engineering provides a powerful means to tailor the spectral response and electrical characteristics of CdTe-based photodetectors. By selecting appropriate partner materials and controlling interface properties, key parameters such as dark current, responsivity, response time, and noise characteristics can be optimized. Heterojunction structures also help suppress surface-related recombination and contact-induced losses, which are often major limitations in single-layer photodetectors [2]. As a result, CdTe heterojunction photodetectors exhibit superior performance compared to simple metal–semiconductor or homojunction devices. Owing to these advantages, CdTe heterojunction photodetectors have been extensively investigated for applications ranging from visible-light imaging and optical communication to radiation detection and spectroscopy. Continuous advances in materials

engineering, interface passivation, and device design have further expanded their performance limits, making CdTe heterojunction systems a compelling platform for next-generation photodetection technologies [3].

II. HETEROJUNCTION CONCEPTS IN PHOTODETECTORS

A heterojunction is formed when two dissimilar semiconductor materials with different bandgaps, electron affinities, and carrier concentrations are brought into intimate contact. Unlike homojunctions, where the junction is created within the same semiconductor material, heterojunctions offer greater flexibility in tailoring electronic and optical properties through appropriate material selection and interface engineering. This flexibility makes heterojunctions particularly attractive for high-performance photodetector applications [3], [4], [5].

In photodetectors, the primary role of a heterojunction is to enhance the efficiency of photocarrier generation, separation, and collection. When a heterojunction is formed, differences in the Fermi levels of the constituent semiconductors lead to charge transfer across the interface until thermal equilibrium is established. This charge redistribution creates a built-in electric field in the vicinity of the junction. The built-in field plays a critical role in separating photogenerated electron–hole pairs and driving them toward their respective electrodes without the need for an externally applied bias. As a result, heterojunction photodetectors often exhibit higher responsivity and lower recombination losses compared to devices based on simple metal–semiconductor contacts. Another important advantage of heterojunctions is the suppression of recombination at the electrical contacts. In many photodetector architectures, direct metal contacts can introduce interface states that act as recombination centers, increasing dark current and noise. By inserting a wide-bandgap semiconductor as a window or buffer layer, the heterojunction effectively blocks minority carriers from reaching the metal contact while allowing majority carriers to be collected efficiently. This selective carrier transport reduces leakage current and enhances the signal-to-noise ratio, which is crucial for low-light detection [6], [7].

Heterojunctions also enable precise control over band alignment, allowing the spectral response of photodetectors to be tailored for specific wavelength ranges. By choosing materials with appropriate bandgaps and band offsets, it is possible to engineer devices that are sensitive to visible, near-infrared, or ultraviolet radiation. This tunability is especially important in CdTe-based photodetectors, where the absorber layer can be paired with different window materials to optimize optical transparency, carrier transport, and interface stability. The electronic behavior of a heterojunction is largely governed by its band alignment, which is generally classified into three types: Type I (straddling gap), Type II (staggered gap), and Type III (broken gap). In Type I heterojunctions, both the conduction band minimum and valence band maximum of one semiconductor lie within the bandgap of the other, resulting in carrier confinement in the

narrower bandgap material. While this configuration is beneficial for light-emitting devices, it can limit carrier separation in photodetectors [8], [9].

Type II heterojunctions, also known as staggered band alignments, are particularly advantageous for photodetection. In this configuration, the conduction band minimum and valence band maximum are offset such that electrons and holes are spatially separated across the interface. This spatial separation significantly reduces the probability of electron–hole recombination, thereby extending carrier lifetimes and improving photocurrent generation. Consequently, Type II heterojunctions often exhibit enhanced responsivity, faster response times, and improved stability, making them highly suitable for CdTe-based photodetectors [10].

Type III heterojunctions feature a broken band alignment, where the conduction band of one material lies below the valence band of the other. Although such structures are mainly explored for tunneling and high-speed electronic devices, their application in photodetectors is relatively limited due to increased leakage currents and complex transport mechanisms. In summary, heterojunction engineering provides a powerful framework for optimizing photodetector performance by enabling efficient charge separation, minimizing recombination losses, and allowing spectral and electrical tuning through band alignment control. For CdTe heterojunction photodetectors, careful selection of partner materials and precise control of interface quality are essential to fully exploit the advantages offered by heterojunction device architectures [8], [10].

➤ *Band Alignment and Energy Band Diagrams*
The performance of a heterojunction photodetector is fundamentally governed by the relative alignment of the energy bands at the interface between the two semiconductors. Band alignment determines the height of potential barriers, the direction of carrier flow, and the efficiency of photogenerated charge separation. In CdTe heterojunction photodetectors, careful control of band offsets is essential for minimizing recombination losses and maximizing photocurrent [11].

➤ *Energy Band Parameters*
The key parameters defining band alignment include the electron affinity (χ), bandgap energy (Eg), and work function (Φ) of each semiconductor. When two materials are brought into contact, their Fermi levels align at equilibrium, resulting in band bending near the interface. The conduction band offset (ΔEc) and valence band offset (ΔEv) at the heterojunction interface can be approximated using the Anderson (electron affinity) model [12]:

$$\Delta Ec = \chi_2 - \chi_1$$

$$\Delta Ev = (Eg_2 - Eg_1) - \Delta Ec$$

where subscripts 1 and 2 refer to the two semiconductors forming the heterojunction. These band offsets determine the ease with which electrons and holes can cross the interface under illumination. In CdTe-based

photodetectors, CdTe typically serves as the narrow-bandgap absorber, while a wider-bandgap semiconductor such as CdS or ZnO acts as the window layer. This configuration ensures strong light absorption in CdTe while maintaining high optical transparency in the window layer [13].

➤ *Band Diagrams Before and After Contact*

Before contact, each semiconductor has its own independent energy band structure, characterized by distinct conduction band minima, valence band maxima, and Fermi levels. Due to differences in work function and carrier concentration, the Fermi level of the n-type window layer (e.g., CdS) lies closer to the conduction band, while the Fermi level of p-type CdTe is positioned nearer to the valence band [14].

After contact, charge transfer occurs across the interface until a common Fermi level is established. Electrons diffuse from the n-type material into the p-type CdTe, while holes move in the opposite direction. This diffusion results in the formation of a depletion region on both sides of the junction and induces band bending near the interface. The built-in potential created across the depletion region generates an internal electric field that drives photogenerated electrons toward the n-type layer and holes toward the p-type CdTe [15].

In energy band diagrams, this behavior is represented by the bending of the conduction and valence bands near the junction, with the magnitude of bending corresponding to the built-in voltage of the heterojunction.

➤ *Type I, Type II, and Type III Band Alignments*

Energy band diagrams are commonly used to visualize three fundamental types of heterojunction band alignment:

• *Type I (Straddling Gap):*

In this configuration, the conduction band minimum and valence band maximum of one semiconductor lie entirely within the bandgap of the other. Both electrons and holes are confined in the narrower-bandgap material. While advantageous for light-emitting devices, this confinement can limit carrier separation in photodetectors and increase recombination probability [8].

• *Type II (Staggered Gap):*

Type II alignment is the most desirable configuration for photodetectors. Here, the conduction band minimum of one material lies lower than that of the other, while the valence band maximum lies higher in the opposite material. As a result, electrons and holes are spatially separated across the heterojunction interface. In CdTe heterojunction photodetectors, this staggered alignment promotes efficient charge separation, suppresses interfacial recombination, and enhances carrier lifetime, leading to higher responsivity and improved detectivity [7].

• *Type III (Broken Gap):*

In Type III alignment, the conduction band of one semiconductor lies below the valence band of the other,

resulting in a broken bandgap. Such structures allow tunneling-dominated transport and are mainly explored in high-speed electronic and tunneling devices. Their application in photodetectors is limited due to high leakage currents and complex carrier dynamics [16].

➤ *Band Diagram Under Illumination*

Under optical illumination, photons with energy greater than the bandgap of CdTe generate electron–hole pairs within the absorber layer. The built-in electric field at the heterojunction interface separates these carriers before they can recombine. Electrons are swept toward the n-type window layer, while holes are transported toward the p-type CdTe contact. This directional carrier flow is clearly depicted in illuminated band diagrams, where quasi-Fermi levels split, indicating nonequilibrium carrier populations. The efficiency of this process depends strongly on the height of band offsets and the quality of the heterojunction interface. Excessively large conduction or valence band barriers can impede carrier transport, while insufficient offsets may lead to increased recombination. Therefore, optimal band alignment is critical for achieving high-performance CdTe heterojunction photodetectors [2].

➤ *Relevance to CdTe Heterojunction Systems*

Common CdTe heterojunctions such as CdS/CdTe, ZnO/CdTe, and CdSe/CdTe typically exhibit near-Type II or weak Type I band alignment, which is favorable for photodetection. Proper interface engineering, including surface passivation and graded bandgap layers, further improves band alignment and reduces interface trap densities. In summary, energy band alignment and its graphical representation through band diagrams provide essential insight into carrier transport mechanisms in heterojunction photodetectors. For CdTe-based devices, optimized band offsets and well-engineered interfaces are key to achieving efficient charge separation, low dark current, and high photodetection efficiency [17].

III. DEVICE ARCHITECTURES

The performance of CdTe-based photodetectors is strongly influenced by device architecture, which determines carrier generation, separation, transport, and collection efficiency. Various heterostructure designs have been explored to optimize responsivity, dark current, response speed, and operational stability. Among these, p–n heterojunction photodiodes, Schottky photodiodes, and PIN and avalanche photodetectors represent the most widely investigated architectures [18].

➤ *p–n Heterojunction Photodiodes*

p–n heterojunction photodiodes are the most extensively studied and commercially relevant CdTe photodetector structures. These devices are typically fabricated by depositing p-type CdTe onto an n-type wide-bandgap semiconductor that acts as a window or buffer layer. Commonly used n-type materials include CdS, ZnO, and CdSe, owing to their high optical transparency in the visible region and favorable band alignment with CdTe.

The heterojunction formed at the p–n interface generates a built-in electric field as a result of carrier diffusion and band bending. Under illumination, photons absorbed in the CdTe layer generate electron–hole pairs, which are efficiently separated by this internal electric field. Electrons are driven toward the n-type window layer, while holes are transported through the p-type CdTe toward the back contact. This efficient carrier separation minimizes recombination losses and leads to enhanced photocurrent generation [19].

Typical p–n heterojunction structures include:

- n-CdS / p-CdTe, the most widely used configuration due to good lattice matching and well-established fabrication protocols
- n-ZnO / p-CdTe, offering higher transparency and improved short-wavelength response
- n-CdSe / p-CdTe, providing extended spectral sensitivity and improved band alignment in certain device designs

The primary advantages of p–n heterojunction photodiodes include low operating voltage, relatively low dark current, high responsivity, and compatibility with large-area thin-film deposition techniques. However, device performance can be limited by interface defects and lattice mismatch, which introduce trap states that act as recombination centers. Consequently, interface engineering and surface passivation play a crucial role in optimizing these devices [20].

➤ Schottky Photodiodes

Schottky photodiodes are formed by creating a rectifying metal–semiconductor junction between CdTe and a suitable metal contact. Metals such as gold (Au), platinum (Pt), and nickel (Ni) are commonly used to form Schottky barriers on CdTe due to their high work functions. The metal–CdTe interface establishes a depletion region within the semiconductor, where an internal electric field exists. In Schottky photodetectors, incident photons absorbed near the depletion region generate electron–hole pairs that are rapidly separated by the built-in field. Because the depletion region is typically narrow, these devices exhibit fast response times and high-frequency operation, making them attractive for applications requiring rapid signal detection. One of the key advantages of Schottky photodiodes is their relatively simple fabrication process compared to p–n heterojunctions. Additionally, the barrier height can be tuned by selecting appropriate metals or introducing interfacial layers, allowing some control over device characteristics. Despite these advantages, Schottky CdTe photodetectors often suffer from higher dark current compared to p–n heterojunction devices. This increased leakage current arises from thermionic emission and tunneling mechanisms at the metal–semiconductor interface, particularly under reverse bias. As a result, achieving effective dark current suppression remains a significant challenge, necessitating careful optimization of contact materials and interface quality [21].

➤ PIN Photodiodes and Avalanche Photodetectors (APDs)

PIN photodiodes represent an advanced architecture designed to improve quantum efficiency and carrier collection efficiency. In these devices, an intrinsic or lightly doped CdTe layer is inserted between the p-type and n-type regions, significantly increasing the depletion width. The expanded depletion region enhances light absorption and reduces carrier recombination, resulting in improved responsivity and reduced capacitance.

In CdTe PIN photodetectors, the intrinsic CdTe layer serves as the primary absorption region, while the p-type and n-type layers provide efficient carrier extraction. These devices typically operate at higher reverse bias voltages than simple p–n junctions but offer superior performance in terms of sensitivity and noise characteristics. PIN architectures are particularly suitable for applications requiring high detection accuracy and stable operation under varying illumination conditions.

Avalanche photodetectors (APDs) extend the PIN concept by exploiting the impact ionization phenomenon to achieve internal signal amplification. Under high electric fields, charge carriers gain sufficient kinetic energy to generate additional electron–hole pairs through collisions, leading to avalanche multiplication. This internal gain allows APDs to detect extremely weak optical signals, making them suitable for low-light and photon-counting applications. Although CdTe-based APDs offer the advantage of high gain and improved detectivity, their practical implementation is challenging. Issues such as high operating voltages, excess noise due to stochastic avalanche processes, and long-term device stability must be carefully addressed. Nevertheless, ongoing research into material quality improvement and electric field engineering continues to advance the feasibility of CdTe APDs [22].

IV. PERFORMANCE METRICS

The performance of CdTe heterojunction photodetectors is evaluated using several key parameters that describe their sensitivity, speed, and noise characteristics. These metrics provide quantitative insight into device efficiency and are critical for comparing different material systems, device architectures, and fabrication techniques.

➤ Responsivity (R)

Responsivity is one of the most important parameters of a photodetector, as it quantifies the electrical output generated per unit of incident optical power. It is defined as [23]:

$$R = \frac{I_{ph}}{P_{opt}}$$

where I_{ph} is the photocurrent and P_{opt} is the incident optical power. Responsivity is typically expressed in units of amperes per watt (A/W). High responsivity indicates efficient photocarrier generation, separation, and collection within the device. In CdTe heterojunction photodetectors, responsivity values exceeding 0.3 A/W in the visible region are commonly

reported, reflecting the strong optical absorption and favorable band alignment of CdTe. Responsivity depends on several factors, including the absorption coefficient of the active layer, carrier mobility, depletion width, and interface quality. Optimization of heterojunction interfaces and contact engineering plays a crucial role in minimizing recombination losses and maximizing responsivity.

Theoretical responsivity is also related to quantum efficiency by [24]:

$$R = \frac{q\lambda}{hc} X \, \eta$$

where q is the electronic charge, λ is the wavelength of incident light, h is Planck's constant, c is the speed of light, and η is the quantum efficiency.

➢ *Quantum Efficiency (QE)*

Quantum efficiency (QE) represents the ratio of the number of charge carriers collected by the photodetector to the number of incident photons. It provides a direct measure of the photodetection efficiency and is expressed as [25]:

$$QE = \frac{\text{Number of collected carriers}}{\text{Number of incident photons}}$$

QE can be categorized into external quantum efficiency (EQE) and internal quantum efficiency (IQE). EQE accounts for optical losses such as reflection and incomplete absorption, whereas IQE considers only the efficiency of carrier generation and collection within the absorber layer. In optimized CdTe heterojunction photodetectors, internal quantum efficiency can approach unity, indicating that nearly every absorbed photon contributes to the photocurrent. High QE is achieved through strong light absorption in CdTe, effective built-in electric fields at the heterojunction interface, and minimal recombination at grain boundaries and interfaces. The use of wide-bandgap window layers further enhances QE by allowing maximum photon transmission into the CdTe absorber.

➢ *Dark Current and Noise*

Dark current is the current that flows through a photodetector in the absence of illumination. It arises from thermally generated carriers, leakage through defects, and tunneling mechanisms at junctions and contacts. Minimizing dark current is essential for achieving a high signal-to-noise ratio (SNR), particularly in low-light detection applications. In CdTe heterojunction photodetectors, dark current is strongly influenced by device architecture, material quality, and interface states. p–n heterojunction devices typically exhibit lower dark current compared to Schottky photodiodes due to better carrier blocking at the junction. Interface defects and grain boundary states act as generation–recombination centers, increasing leakage current and noise. Noise in photodetectors originates from several sources, including thermal (Johnson) noise, shot noise, and flicker (1/f) noise. Shot noise, which is directly proportional to dark current, often dominates in CdTe devices. Therefore, reducing dark

current through improved material crystallinity, interface passivation, and optimized contact design is crucial for enhancing detectivity [10].

➢ *Response Time and Bandwidth*

Response time describes how quickly a photodetector can respond to changes in incident light intensity, while bandwidth defines the frequency range over which the device can operate effectively. These parameters are governed by carrier transit time, junction capacitance, and external circuit resistance. In CdTe heterojunction photodetectors, response time is primarily limited by the mobility of charge carriers and the width of the depletion region. Thinner absorber layers and stronger internal electric fields enable faster carrier extraction, leading to shorter rise and fall times. Junction capacitance, which depends on device geometry and depletion width, also plays a significant role in determining bandwidth. CdTe-based photodetectors typically support bandwidths in the MHz range, making them suitable for applications such as imaging systems, optical communication receivers, and real-time sensing. Advanced architectures, including Schottky and PIN photodiodes, can further enhance response speed by reducing carrier transit time and parasitic capacitance.

V. CONCLUSION

CdTe heterojunction photodetectors constitute one of the most extensively investigated and technologically relevant classes of II–VI semiconductor–based optoelectronic devices. Owing to its direct and near-ideal band gap (~1.45 eV), high optical absorption coefficient, and long carrier diffusion lengths, CdTe offers an exceptional platform for efficient visible to near-infrared photodetection. When integrated into heterojunction architectures with wide-band-gap window layers such as CdS, ZnO, ZnSe, or emerging two-dimensional materials, CdTe enables strong built-in electric fields that promote effective charge separation, low recombination losses, and high quantum efficiency. This review has highlighted the critical role of band alignment, interface quality, and device architecture in determining photodetector performance. Type-II band alignment in particular has proven advantageous for suppressing dark current while enhancing photocurrent generation, making CdTe heterojunctions well suited for low-noise and self-powered photodetection. Advances in Schottky and PIN configurations further demonstrate the versatility of CdTe in addressing application-specific requirements such as high-speed response, broadband sensitivity, and low-light detection. Moreover, the integration of CdTe into avalanche photodiodes and hybrid heterostructures opens new pathways for internal gain mechanisms and enhanced detectivity. Despite these advantages, several challenges remain that must be addressed to fully exploit the potential of CdTe heterojunction photodetectors. Interface defects, lattice mismatch, and deep-level trap states continue to limit carrier lifetime and long-term stability, particularly in solution-processed and low-temperature fabricated devices. In this context, interface engineering strategies—including passivation layers, graded junctions, band-offset tuning, and surface chemical

treatments—are emerging as key tools for performance optimization. Additionally, controlled doping, compositional engineering (e.g., CdHgTe or doped CdTe alloys), and thickness optimization offer further opportunities to tailor spectral response and reduce noise. Looking forward, the convergence of CdTe with advanced materials systems, such as perovskites, two-dimensional semiconductors, and flexible substrates, is expected to expand its applicability in next-generation photodetection platforms. Developments in scalable, low-cost deposition techniques combined with improved device modeling and in-situ characterization will accelerate the transition of CdTe heterojunction photodetectors from laboratory prototypes to commercially viable technologies. Overall, CdTe remains a robust and adaptable semiconductor whose continued evolution promises impactful contributions to imaging, optical communication, environmental monitoring, and radiation sensing applications.

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