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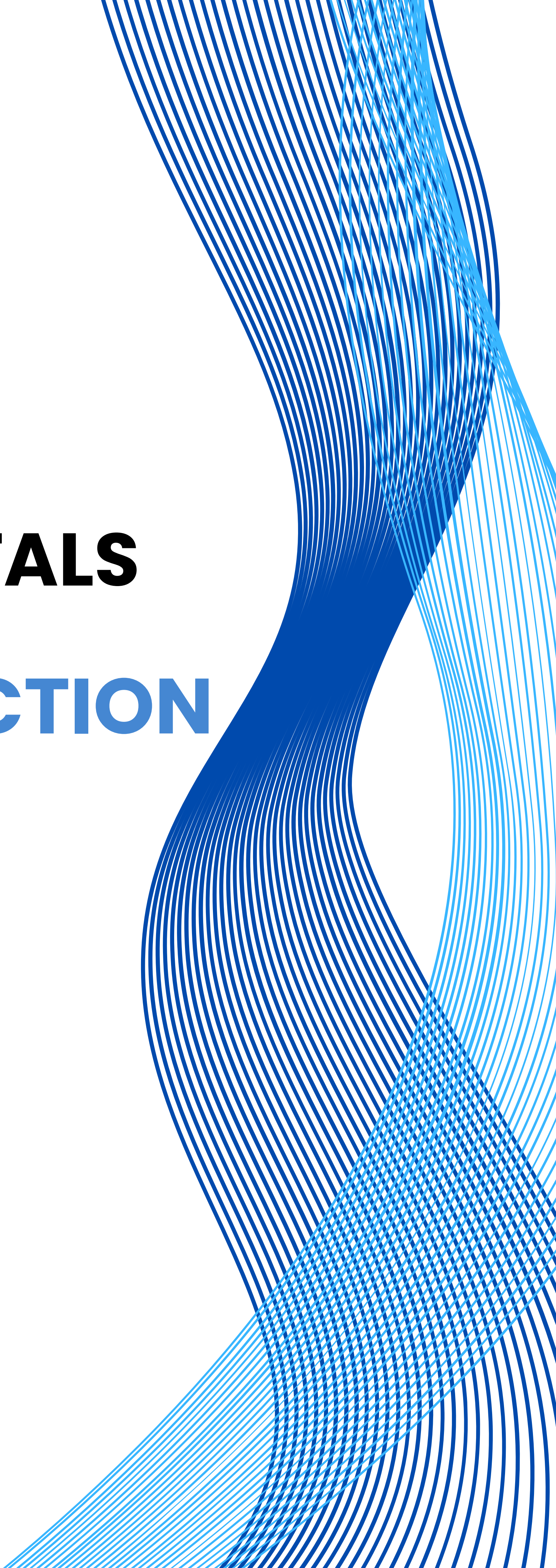
OPTOELECTRONICS



FUNDAMENTALS OF LIGHT DETECTION

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WHAT IS LIGHT?

An Overview of the Electromagnetic Spectrum

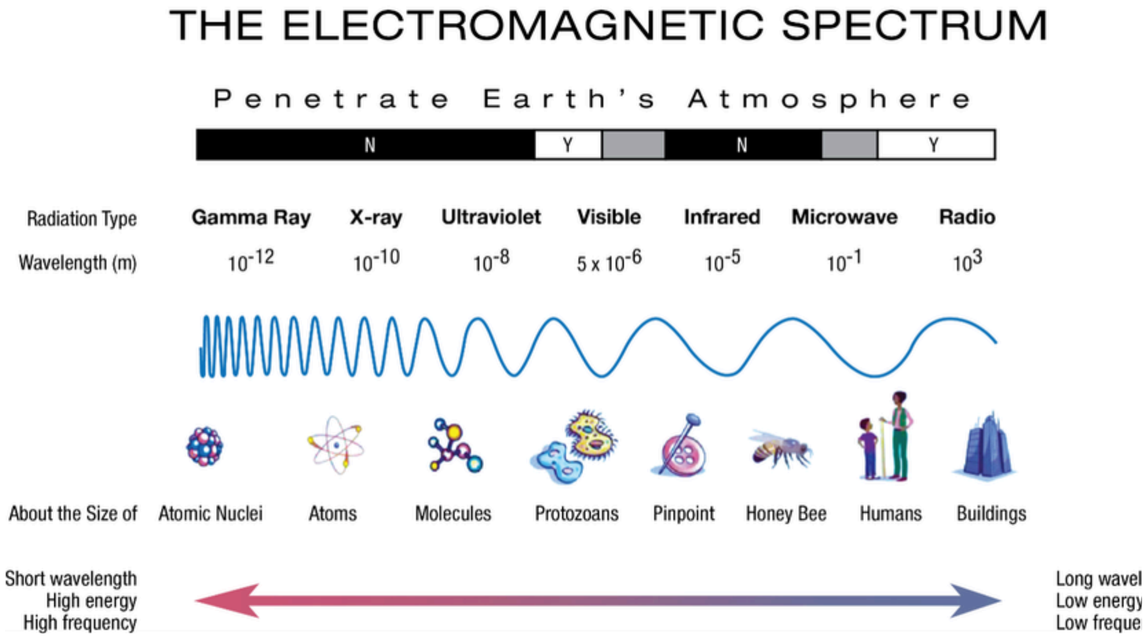
Light is a form of electromagnetic radiation, which is energy that travels through space in the form of waves or particles called photons. Electromagnetic radiation encompasses a vast range of wavelengths and frequencies, collectively known as the electromagnetic spectrum. This spectrum includes everything from high-energy gamma rays to low-energy radio waves, with visible light occupying only a small portion in the middle.

The electromagnetic spectrum is typically divided into regions based on wavelength (λ), frequency (f), and energy (E). The relationship between these properties is given by two fundamental equations:

- Speed of light: $c = \lambda * f$, where c is the speed of light in vacuum (approximately 3×10^8 m/s). This shows that wavelength and frequency are inversely proportional—as wavelength increases, frequency decreases, and vice versa.
- Energy of a photon: $E = h * f = h * c / \lambda$, where h is Planck's constant (6.626×10^{-34} J·s). Higher frequency (shorter wavelength) corresponds to higher energy.

The spectrum spans wavelengths from less than 10^{-12} meters (gamma rays) to more than 10^3 meters (radio waves). Key regions include:

- Gamma Rays and X-Rays: Wavelengths < 10 nm (f > 30 PHz, E > 124 eV). High-energy radiation used in medical imaging (X-rays) and cancer treatment (gamma rays). Penetrates matter deeply but ionizes atoms, posing health risks.
- Ultraviolet (UV): 10–400 nm (f = 0.75–30 PHz, E = 3–124 eV). Causes sunburn and fluorescence; used in sterilization and photolithography. Divided into UVA (315–400 nm), UVB (280–315 nm), and UVC (100–280 nm).
- Visible Light: 400–700 nm (f = 430–750 THz, E = 1.77–3.1 eV). The range detectable by the human eye, from violet (short λ) to red (long λ). Essential for vision, photography, and displays.
- Infrared (IR): 700 nm–1 mm (f = 300 GHz–430 THz, E = 1.24 meV–1.77 eV). Felt as heat; used in thermal imaging, remote controls, and fiber optics. Subdivided into near-IR (0.7–5 μm), mid-IR (5–30 μm), and far-IR (30 μm–1 mm).
- Microwaves: 1 mm–1 m (f = 300 MHz–300 GHz, E = 1.24 μeV–1.24 meV). Used in radar, cooking, and wireless communications (e.g., Wi-Fi).
- Radio Waves: >1 m (f < 300 MHz, E < 1.24 μeV). Employed in broadcasting, navigation (GPS), and astronomy.



[Figure 1: The Electromagnetic Spectrum Source: NASA]

Electromagnetic waves are transverse, with oscillating electric and magnetic fields perpendicular to the direction of propagation. In detection contexts, understanding the spectrum helps select photodiodes sensitive to specific regions, such as GPD's InGaAs for extended IR up to 2.6 μm.

Introduction to Light Detection

Light detection plays a pivotal role in modern technology, enabling everything from optical communications and medical diagnostics to industrial sensing and scientific research. At its essence, light detection converts photonic energy into electrical signals using devices like photodiodes, which offer high sensitivity, rapid response, and broad spectral coverage. This guide focuses on the fundamentals of photodiodes, their operational principles, and practical design strategies for integrating them into systems. Drawing from key concepts in optics, radiometry, and electronics, it equips designers with the knowledge to optimize performance in applications such as spectroscopy, beam alignment, and low-light imaging.

Unlike light emission technologies, detection emphasizes absorption and conversion efficiency. Photodiodes, particularly silicon-based ones, dominate due to their versatility, low cost, and compatibility with visible to near-infrared wavelengths (approximately 250–1100 nm). This document explores photodiode types, parameters, circuit designs, and applications, providing a comprehensive resource for engineers at trade shows or in product development.

Published by GPD Optoelectronics Corp., a leading manufacturer of Ge, Si, and InGaAs photodiodes with responsivity ranging from 250 nm to 2.6 microns (www.gpd-ir.com). In addition to single-element photodiodes, GPD offers quadrant and octo-cell variants, as well as tetralateral position-sensing detectors, which enable precise beam positioning without gaps.

What is a Photodiode?

A photodiode is a semiconductor device that converts incident light into electrical current via the photoelectric effect. It consists of a PN junction where photons absorbed in the depletion region generate electron-hole pairs, producing a photocurrent proportional to light intensity.

Unlike standard diodes, photodiodes feature a large active area optimized for light absorption, often with an anti-reflection coating to enhance efficiency at specific wavelengths.

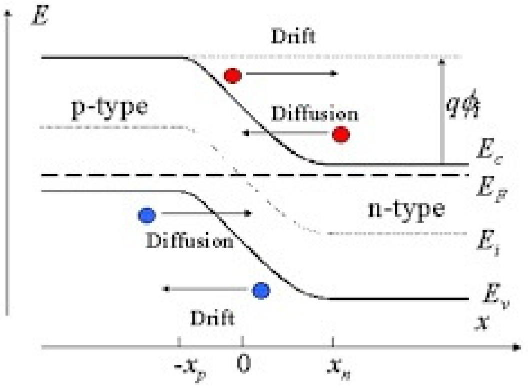
Understanding the PN Junction

A PN junction is formed by joining two types of semiconductor materials: P-type and N-type. [1] In N-type material, silicon is doped with impurities like antimony, introducing free electrons as the majority charge carriers while maintaining overall electrical neutrality. In P-type material, silicon is doped with boron, creating holes (absence of electrons) as the majority carriers, again keeping the material neutral. [1]

When the P-type and N-type materials are fused together, a density gradient arises due to the higher concentration of electrons in the N-region and holes in the P-region. This leads to diffusion: free electrons from the N-side migrate across the junction to the P-side, where they recombine with holes, while holes from the P-side diffuse to the N-side and recombine with electrons. [1] As this diffusion occurs, the recombined carriers leave behind fixed ionized impurities—positively charged donor ions (N_D) on the N-side and negatively charged acceptor ions (N_A) on the P-side. [1]

PN Junction Continued :

This charge separation creates a region around the junction depleted of mobile charge carriers (electrons and holes), known as the depletion region. [1] The width of this region depends on the doping levels, satisfying charge neutrality: D_p · N_A = D_n · N_D, where D_p and D_n are the penetration depths into the P- and N-sides, respectively. [1]



The fixed ions in the depletion region establish an internal electric field directed from the positively charged N-side to the negatively charged P-side. [1] This field creates a built-in potential barrier (E_o), calculated as E_o = V_T · ln((N_D · N_A) / n_i²), where V_T is the thermal voltage (~26 mV at room temperature), N_D and N_A are doping concentrations, and n_i is the intrinsic carrier concentration. [1] For silicon, this barrier is about 0.6–0.7 V at room temperature. [1]

This electric field and potential barrier allow current to flow preferentially in one direction (forward bias) while opposing it in the opposite direction (reverse bias), giving the junction its rectifying (diode-like) behavior. [1] In forward bias, an external voltage reduces the barrier height, enabling majority carriers to cross and sustain current flow. In reverse bias, the barrier increases, preventing majority carrier flow and imiting current to a small leakage (minority carriers aided by the field). [1]

Other Junction Variations:

- PIN Diodes: PIN photodiodes feature an intrinsic (I) layer between the P-type and N-type regions, creating a wider depletion region compared to PN diodes. This intrinsic layer, undoped or lightly doped, enhances the electric field strength and reduces junction capacitance, enabling faster response times (up to GHz ranges). When light strikes the I-layer, photon-generated electron-hole pairs are efficiently separated by the field, producing a photocurrent proportional to the incident light intensity. PIN diodes are widely used in high-speed applications like fiber-optic communications due to their low noise and high bandwidth, typically operated in photoconductive mode with reverse bias (5–10V) to optimize performance [1].

- Avalanche Photodiodes (APDs): APDs operate under high reverse bias, where the electric field in the depletion region is strong enough to cause impact ionization. This process occurs when a photon-generated electron (or hole) gains sufficient energy to create additional electron-hole pairs upon collision with the lattice, leading to an internal current gain (multiplication factor up to 1000x). This gain enhances sensitivity for low-light detection, making APDs ideal for applications like lidar and medical imaging. However, the high bias increases dark current and noise, requiring careful design and cooling. The avalanche effect is controlled by the avalanche effect is controlled by the material’s bandgap and doping profile, with silicon and InGaAs being common choices [1].

Common materials include silicon (Si) for UV to NIR (250–1100 nm), germanium (Ge) for NIR (800–1800 nm), and indium gallium arsenide (InGaAs) for extended NIR (up to 2.6 μm). GPD Optoelectronics Corp. specializes in these materials, providing high-performance photodiodes tailored for demanding applications. Silicon photodiodes are prevalent due to low dark current, high speed, and cost-effectiveness. The basic structure involves a P-type layer diffused into an N-type substrate, forming a depletion region that expands under reverse bias for improved performance.

How Photodiodes Work

Photodiodes operate on the principle of photon absorption in a semiconductor, where photon energy exceeding the bandgap (1.12 eV for silicon) excites electrons from the valence to conduction band. This creates charge carriers swept across the junction by the built-in electric field, generating current.

Key operational modes include:

- Photovoltaic Mode (Zero Bias): No external voltage; the device generates voltage like a solar cell. Ideal for low-speed, low-noise applications (e.g., light meters). Dark current is minimal, but response time is slower due to higher junction capacitance.

Photoconductive Mode (Reverse Bias): External reverse bias widens the depletion region, reducing capacitance and improving speed

linearity. Increases responsivity but elevates dark current and noise. Common in high-speed scenarios like optical communications.

- Avalanche Mode: High reverse bias induces carrier multiplication via impact ionization in avalanche photodiodes (APDs). Provides internal gain (up to 1000x) for low-light detection, though with higher noise.

The photocurrent (I_PD) is I_PD = R_λ * P, where R_λ is responsivity (A/W) and P is incident power. Responsivity peaks at ~0.5–0.6 A/W for silicon at 900 nm, varying with wavelength and bias. GPD’s Ge, Si, and InGaAs photodiodes achieve high responsivity across 250 nm to 2.6 microns, making them suitable for broadband detection.

Types of Photodiodes

Photodiodes are categorized by structure and material:

- Schottky Photodiodes: Metal-semiconductor junction for UV detection; low noise, fast response.

Material comparisons:
• Silicon: Low dark current, high speed, visible-NIR, low cost.
• Germanium: High dark current, NIR, moderate cost.
• InGaAs: Low dark current, high speed, NIR-MIR, higher cost.

GPD’s portfolio includes these materials in single-element, quadrant, octo-cell, and tetralateral configurations.

Key Parameters & Characteristics

Photodiodes are categorized by structure and material:

- [1Responsivity (R_λ): Photocurrent per unit power; peaks in material-specific ranges. Temperature coefficient ~0.1–0.2%/°C. GPD photodiodes offer responsivity up to 1.5 A/W in InGaAs for 2.6 μm detection.

- Dark Current (I_D): Leakage without light; doubles every 10°C increase. Minimized in photovoltaic mode.
- Noise Equivalent Power (NEP): Minimum detectable power (W/√Hz); lower values indicate better sensitivity. NEP = √(2q I_D Δf + 4kT Δf / R_SH) / R_λ.
- Junction Capacitance (C_J): Inversely proportional to bias; affects bandwidth. C_J = ε A / W_d, where W_d is depletion width.
- Rise/Fall Time: Determines speed; t_r ≈ 0.35 / f_3dB. Limited by drift, diffusion, and RC times.
- Quantum Efficiency (QE): Fraction of photons generating carriers; QE = R_λ * (1240 / λ) %.
- Shunt Resistance (R_SH): High values (>GΩ) reduce noise in photovoltaic mode.

For multi-element devices like GPD's quadrant and tetralateral PSDs, additional parameters include position resolution (e.g., <1 μm) and linearity across the active area.

Temperature impacts: Responsivity shifts with bandgap changes; cooling extends spectral range but increases resistance.

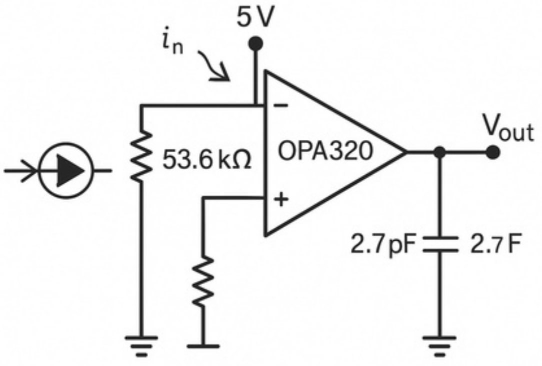
Circuit Design with Photodiodes

Amplifying weak photocurrents requires careful circuit design, typically using transimpedance amplifiers (TIAs) to convert current to voltage: V_out = -I_PD * R_F.

Basic TIA Design

1. Op-Amp Selection: Low input bias current (e.g., <1 pA), high gain-bandwidth product (GBW > 10 MHz), low noise (e.g., OPA320).
2. Feedback Resistor (R_F): Sets gain; balances sensitivity and bandwidth. For 1 MHz bandwidth, R_F ≈ 50 kΩ.
3. Feedback Capacitor (C_F): Stabilizes by compensating input capacitance. C_F ≈ √(C_IN / (2π GBW R_F)), where C_IN includes diode and amp capacitances.

4..Biasing: In single-supply setups, apply small positive bias (e.g., 100 mV) to non-inverting input to avoid saturation. Use resistor divider from V_CC.
5. Noise Mitigation: Shot noise dominates in biased mode; Johnson noise in unbiased. Total noise i_n = √(2q I_PD Δf + 4kT Δf / R_F).



Designs for Multi-Element and Position-Sensing Detectors

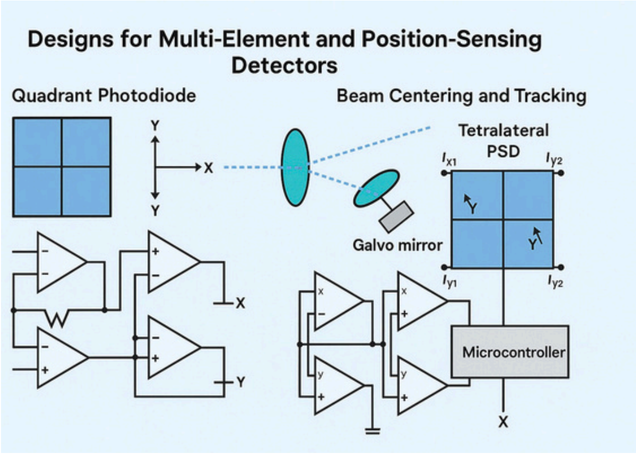
GPD's quadrant and octo-cell photodiodes are used for beam centering and tracking. In a quadrant detector, four segments provide differential currents (e.g., I_top-left, I_top-right, etc.). Position is calculated as:

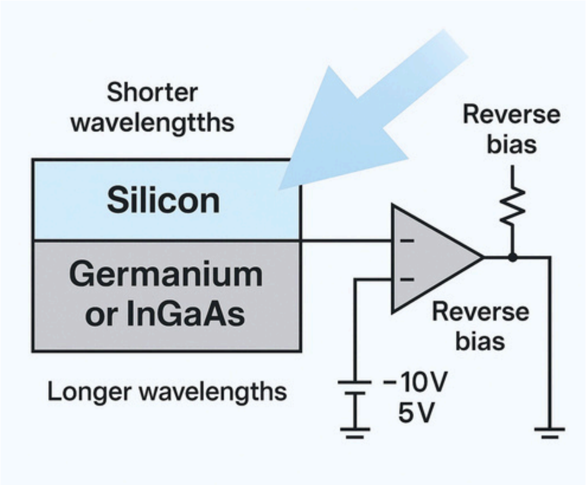
X = (I_right - I_left) / (I_right + I_left)
Y = (I_top - I_bottom) / (I_top + I_bottom)

Circuit: Each quadrant connects to a TIA; outputs feed summing/differencing amps (e.g., using op-amps like OPA2134). For beam steering in free-space optical (FSO) communication, these signals drive servo motors or galvo mirrors to align beams, compensating for atmospheric turbulence on ground links or orbital vibrations in satellite-to-satellite systems.

Tetralateral PSDs from GPD have four electrodes on a single active area, outputting currents proportional to spot position. Position equations:
X = (I_x1 + I_x2 - I_x3 - I_x4) / Total I
Y = (I_y1 + I_y2 - I_y3 - I_y4) / Total I

Circuit: Four TIAs amplify outputs; analog or digital processing (e.g., microcontroller) computes position. In FSO, this enables sub-micron precision for maintaining links over kilometers (ground) or thousands of km (space). Bias PSDs at 5–10V reverse for speed; use low-noise amps to minimize position error.





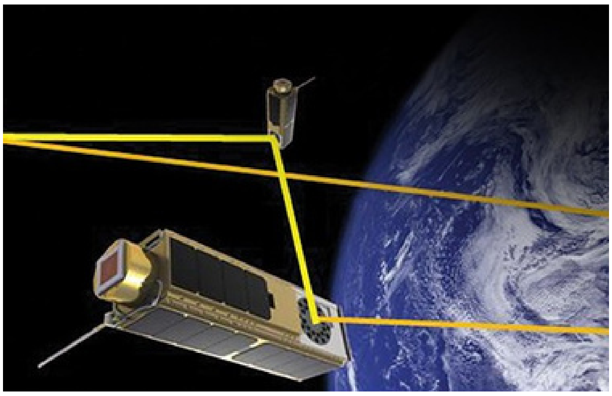
Sandwich Detectors

Sandwich detectors, such as those offered by GPD Optoelectronics Corp., consist of stacked photodiodes (e.g., Si over Ge or InGaAs over InGaAs) designed to detect two spectral bands simultaneously along the same optical path. The top layer absorbs shorter wavelengths and transmits longer ones to the bottom layer, enabling applications like two-color detection and ratio pyrometry for temperature measurement, as well as enhanced sensitivity in multi-band sensing. These detectors, with specifications including low dark current and high responsivity (up to 1.5 A/W for InGaAs), are operated in photoconductive mode with reverse bias (5–10V) for optimal performance [1].

Applications

Optical Communications

PIN/APDs for fiber-optic receivers; quadrant/PSDs for FSO beam steering in ground or satellite networks.



Emerging Quantum

computing with SiPMs, autonomous vehicles with lidar. GPD devices excel in FSO for high-bandwidth, secure links and multi-band detection for precise measurements.

Consumer Electronics

Ambient light sensors in displays.

Scientific Instruments

Spectroscopy, laser rangefinders.

Temperature Measurement

Two-color/sandwich detectors for applications like ratio pyrometry in industrial and semiconductor processes.

Industrial Sensing

Barcode scanners, flame detection, position sensors

Selection Guide

Selecting the correct photodiode requires balancing five primary parameters: spectral range, sensitivity, speed, detector geometry, and operating environment. In practice, the best detector is rarely the one with the highest responsivity or the fastest response alone; instead, it is the device whose material, structure, and packaging best match the wavelength range and measurement conditions of the application.

Step 1: Define the Required Wavelength Range

The first and most important decision is the wavelength range that must be detected. The semiconductor material determines the usable spectral range.

- **Silicon (Si)** photodiodes are the preferred choice for ultraviolet, visible, and near-infrared detection from approximately 250 nm to 1100 nm. They provide low dark current, low cost, and excellent performance in applications such as ambient light sensing, visible spectroscopy, barcode scanners, laser alignment, and machine vision.
- **Germanium (Ge)** photodiodes extend farther into the infrared, typically from 800 nm to 1800 nm. Germanium is often selected when a larger detector area is needed at lower cost, particularly around common telecom wavelengths such as 1310 nm and 1550 nm. However, germanium devices generally have higher dark current and more noise than InGaAs.
- **Standard InGaAs** photodiodes are recommended for short-wave infrared (SWIR) detection from approximately 850 nm to 1700 nm. They offer lower dark current, higher speed, and better signal-to-noise ratio than germanium, making them ideal for fiber-optic communications, lidar, spectroscopy, and laser monitoring.
- **Extended InGaAs** photodiodes are required when the application extends beyond 1700 nm, with sensitivity available out to approximately 2.6 µm. These devices are often used in gas sensing, flame detection, thermal measurement, and specialized scientific instrumentation.

If the system must detect more than one spectral band simultaneously, a sandwich detector should be considered. A Si/Ge or InGaAs/InGaAs stacked detector allows shorter wavelengths to be absorbed in the top layer while longer wavelengths pass through to the lower layer, enabling two-color detection or ratio pyrometry.

Step 2: Determine Required Sensitivity

After choosing the wavelength range, the next consideration is how much optical power must be detected.

- For relatively strong optical signals, such as laser alignment, barcode readers, or industrial light sensors, a standard PIN photodiode is usually sufficient.
- For weak optical signals, low-light conditions, or long-distance optical links, an avalanche photodiode (APD) may be necessary. APDs provide internal gain through avalanche multiplication, increasing the output signal by factors of 10 to more than 1000.

APDs are especially useful in:

- Long-range lidar
- Fiber-optic receivers operating at very low power
- Medical imaging
- Laser rangefinding
- Scientific instruments requiring single-photon or near-single-photon sensitivity

The tradeoff is that APDs require high reverse bias voltage, generate more dark current, and typically need temperature stabilization for consistent performance.

Step 3: Evaluate Speed and Bandwidth Requirements

Detector speed is determined primarily by junction capacitance and carrier transit time. High-speed applications generally require small active areas, reverse bias, and low-capacitance structures.

- For low-speed measurements such as light meters or slowly varying process sensors, operate the detector in photovoltaic mode (zero bias). This provides the lowest noise and best stability.
- For moderate- to high-speed measurements, operate the detector in photoconductive mode with reverse bias. Reverse bias widens the depletion region, lowers capacitance, and significantly improves bandwidth.

Typical recommendations are:

Application	**Recommended Detector**
Ambient light sensing	Si photodiode, photovoltaic mode
General optical measurement	PIN photodiode, low reverse bias
Fiber-optic communications	High-speed PIN or APD
GHz-range receivers	Small-area InGaAs PIN or APD
Pulse detection / lidar	APD with reverse bias

As a general rule, larger detector areas collect more light but have higher capacitance and slower response. Smaller detector areas provide higher speed but require better optical alignment.

Step 4: Select the Proper Detector Geometry

The physical arrangement of the detector is often just as important as the semiconductor material.

- **Single-element photodiodes** are best when only total optical power must be measured.
- **Quadrant or octo-cell photodiodes** should be used when the application requires beam centering, alignment, or tracking. These devices generate separate currents from multiple regions, allowing the system to determine the location of the light spot.

Typical uses include:

- Free-space optical communication
- Beam steering
- Laser alignment
- Motion tracking
- Laser alignment
- Motion tracking
- Optical pointing systems

- **Tetralateral position-sensing detectors (PSDs)** are recommended when continuous, high-resolution position measurement is needed. Unlike quadrant detectors, tetralateral PSDs provide analog position information over the entire active area and can achieve sub-micron resolutionare best when only total optical power must be measured.
- **Sandwich detectors** are the best choice when two wavelengths must be measured simultaneously through the same optical path.should be used when the application requires beam centering, alignment, or tracking. These devices generate separate currents from multiple regions, allowing the system to determine the location of the light spot.

Step 5: Consider the Operating Environment

Environmental conditions often determine whether a detector will perform reliably in practice.

Temperature is especially important because dark current increases rapidly with temperature. In most photodiodes, dark current approximately doubles for every 10°C increase in temperature. High-temperature environments may therefore require:

- Thermoelectric cooling (TEC)
- Temperature compensation circuitry
- Larger signal margins
- Careful shielding from thermal radiation

Cooling is particularly beneficial for:

- APDs
- Extended InGaAs detectors
- Very low-light measurements
- Precision spectroscopy and scientific instruments

Other environmental factors to consider include:

- Humidity and package sealing
- Vibration and shock resistance
- Required detector size and optical aperture
- Exposure to sunlight or stray background radiation
- Required operating lifetime and reliability

Practical Selection Summary

1. Determine the wavelength range.
2. Select the material (Si, Ge, InGaAs, or extended InGaAs).
3. Decide whether a standard PIN detector or an APD is required.
4. Choose the detector geometry: single-element, quadrant, PSD, or sandwich.
5. Select photovoltaic or photoconductive operation based on speed and noise requirements.
6. Review environmental conditions and determine whether temperature stabilization or cooling is necessary.
7. Verify the design using circuit simulation tools such as SPICE or TINA-TI before finalizing the hardware.

Following this process ensures that the detector selected is optimized not only for spectral response, but also for system sensitivity, bandwidth, stability, and long-term reliability.

Conclusion

Photodiodes are at the core of modern light detection, enabling precision, speed, and reliability across a wide range of advanced applications. From optical communications and industrial sensing to scientific instrumentation, they provide the foundation for converting light into accurate, actionable data. GPD Optoelectronics Corp.’s portfolio, including multi-element detectors, position-sensing devices, and advanced sandwich configurations, is engineered to support demanding use cases such as free-space optical communications and multi-band measurement. By combining a strong understanding of photodiode physics with thoughtful system integration, engineers can achieve higher performance, greater sensitivity, and more reliable results.

When performance matters, choosing the right partner is just as important as choosing the right technology. GPD brings decades of experience, in-house manufacturing, and the ability to customize solutions to exact specifications. Whether you need high-speed detection, extended infrared sensitivity, or precision position sensing, our team works closely with you to deliver solutions that meet your application requirements. Connect with GPD to discuss your project and discover how our photodiode technologies can help you build smarter, more capable systems.

APPENDIX

Material Properties:
Silicon vs. Germanium vs. InGaAs

The performance of a photodiode is fundamentally dictated by its constituent semiconductor material, which determines the range of light it can detect, its operational speed, and its noise characteristics. The choice of material is governed primarily by its bandgap energy—the minimum energy a photon must possess to excite an electron from the valence band to the conduction band, thereby generating a measurable current.

Silicon (Si)

Silicon is the most prevalent semiconductor due to its low cost, robust heat resistance (operating up to 150∘C), and compatibility with the mature CMOS (Complementary Metal-Oxide-Semiconductor) fabrication processes..

- Bandgap & Spectral Range: Silicon has an indirect bandgap of approximately1.12 eV at room temperature, which allows it to efficiently detect light in the ultraviolet (UV), visible, and near-infrared (NIR) ranges, typically from 250 nm to 1100 nm.

Optimal Operating Characteristics:

- Low Dark Current: Silicon photodiodes exhibit very low dark current, leading to minimal noise, which makes them ideal for sensitive, low-light applications in the visible spectrum.
- High Speed/Low Capacitance: While it is an indirect bandgap material (requiring a thicker absorption layer for full absorption), silicon APDs and PIN . diodes can achieve fast response times due to their naturally lower junction capacitance compared to InGaAs.

High Quantum Efficiency: Silicon can reach extremely high quantum efficiency (QE) (p. 7).

Germanium (Ge)

Germanium was historically the first semiconductor used, and it remains a viable alternative to InGaAs, especially in cost-sensitive applications requiring a large-area detector in the NIR range. GPD Optoelectronics Corp. was founded as Germanium Power Devices Corp., highlighting its long history with the material.

Indium Gallium Arsenide (InGaAs)

InGaAs is a III-V compound semiconductor alloy engineered for high performance in the infrared spectrum.

- IBandgap & Spectral Range: InGaAs typically operates in the short-wave infrared (SWIR) range, covering 850 nm to 1700 nm for standard compositions. By adjusting the alloy composition (e.g., higher Indium content), the cutoff wavelength can be extended further into the mid-infrared (MIR) range (up to 2.6 µm).
- Optimal Operating Characteristics:
- Superior Signal-to-Noise: The key advantage of InGaAs is its low dark current and high shunt resistance, which provide a significantly better signal-to-noise ratio than germanium.

- High Speed: InGaAs is a direct bandgap material, so light is absorbed efficiently in a much thinner layer compared to silicon or germanium. This results in very low capacitance and high-speed operation, with bandwidths reaching the GHz range.

- High Responsivity: GPD Optoelectronics' InGaAs photodiodes can offer responsivity up to1.5 A/W in extended InGaAs for 2.6 µm detection.

Material	Bandgap Type	Typical Wavelength Range	Dark Current	Speed / Capacitance	Heat Resistance
Silicon (Si)	Indirect	250–1100 nm	Very Low	High Speed / Low Cap	Excellent
Germanium (Ge)	Indirect	800–1800 nm	High	Moderate Speed / High Cap	Moderate
InGaAs	Direct	850–1700 nm	Low	Very High Speed / Low Cap	Good
Extended InGaAs	Direct	850 up to 2.6 µm	Moderate	Very High Speed	Good

- **Avalanche Photodiode (APD)**: A photodiode that uses avalanche multiplication to provide internal gain, enhancing sensitivity for low-light detection.

- **Dark Current (I_D): The s**mall electric current that flows through a photodiode in the absence of light, influenced by temperature and bias.

- **Emissivity**: The measure of an object's ability to emit infrared energy, critical in pyrometry.

- **Free-Space Optical (FSO) Communication:** Wireless communication using light to transmit data through the atmosphere or space.

- **Junction Capacitance (C_J)**: The capacitance across the depletion region of a photodiode, affecting its bandwidth.

- **Noise Equivalent Power (NEP)**: The minimum detectable optical power that produces a signal-to-noise ratio of 1 in a 1 Hz bandwidth.

- **Photoconductive Mode:** Operation of a photodiode under reverse bias, improving speed and linearity but increasing dark current.

- **Photovoltaic Mode**: Operation of a photodiode without bias, generating voltage like a solar cell with minimal noise.

- **Position-Sensing Detector (PSD)**: A photodiode with multiple outputs to determine the position of a light spot, such as GPD's tetralateral design.

- **Quantum Efficiency (QE)**: The percentage of incident photons that generate electron-hole pairs in a photodiode.

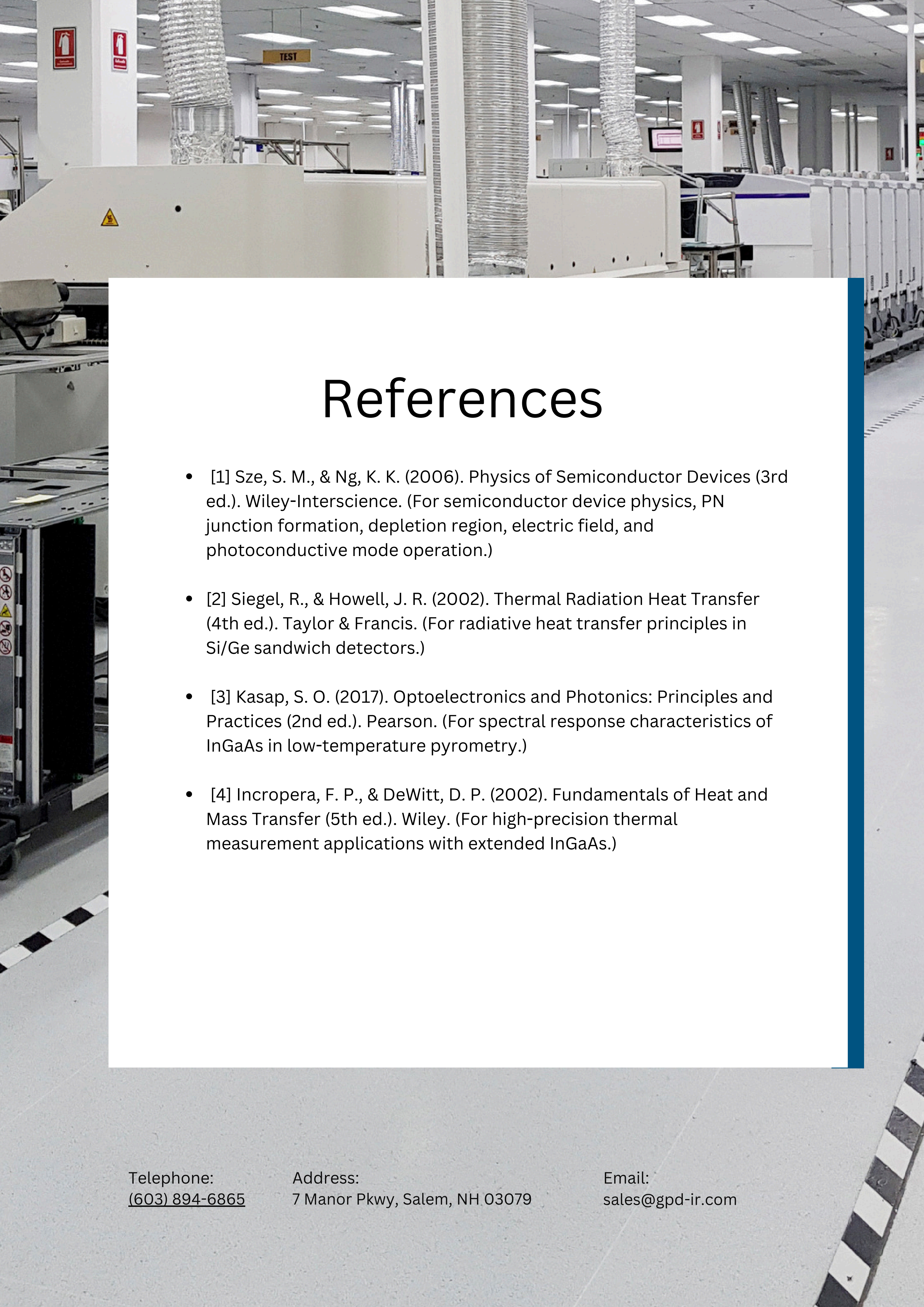
- **Ratio Pyrometry**: A temperature measurement technique using the ratio of intensities at two wavelengths to reduce emissivity errors.

- **Responsivity (R_λ)**: The ratio of photocurrent to incident optical power, measured in amperes per watt (A/W).

- **Sandwich Detector**: A stacked photodiode configuration (e.g., Si over Ge) for simultaneous detection at two wavelengths.

- **Shunt Resistance (R_SH)**: The resistance of a photodiode in the absence of bias, impacting noise performance.

- **Transimpedance Amplifier (TIA):** A circuit that converts photodiode current to a measurable voltage.



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