Application of the Photoelectric Effect in Infrared Remote Sensing Technology

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Abstract: Infrared remote sensing technology plays a vital role in military, geological, agricultural, and medical fields due to its unique advantages. Centered on the theory of the photoelectric effect, this technology converts invisible infrared radiation into electrical signals to enable target detection and data analysis. This review comprehensively examines the applications of the photoelectric effect in infrared remote sensing. It begins with a retrospective analysis of the theoretical evolution of the photoelectric effect, including the fundamental principles of external and internal photoelectric effects, as well as the components and operational mechanisms of infrared remote sensing systems. Subsequently, it focuses on the specific applications of the photoelectric effect in infrared detectors, thermal imaging technology, and spectral analysis, evaluating the performance characteristics and practical scenarios of devices such as HgCdTe detectors, InSb detectors, and quantum well infrared detectors. Finally, by integrating emerging trends in nanomaterials, quantum dot technology, and artificial intelligence (AI), the review envisions future prospects for photoelectric effect applications in infrared remote sensing, including the utilization of novel materials like graphene, optimization of quantum dot infrared detectors, and breakthroughs in intelligent data processing. This work aims to provide readers with a holistic perspective on the integration of photoelectric effects with infrared remote sensing while highlighting its innovative potential across multidisciplinary domains.

1 INTRODUCTION

Infrared remote sensing technology, as a crucial means of acquiring information in modern times, is widely used in military, geological, agricultural, medical, and other related fields, playing a vital role. The core of this technology lies in converting imperceptible infrared radiation signals into detectable electrical signals through the photoelectric effect and processing the data.

The photoelectric effect describes light-induced electron emission from materials. Discovered by Hertz in 1887, it underpins infrared (IR) detector development. As the core of IR remote sensing systems, detector performance, governed by this effect, directly impacts system capabilities. The effect's properties dictate critical detector parameters, including response speed, resolution, sensitivity, and operational wavelength range. This fundamental mechanism enables photoelectric conversion in IR detection, driving advancements in sensing technology.

This study examines the photoelectric effect's implementation in infrared remote sensing, evaluating its strengths and shortcomings while assessing the technology's present state and evolutionary trajectory.

2 THEORY OF PHOTOELECTRIC EFFECT AND INFRARED REMOTE SENSING TECHNOLOGY

2.1 Development History of Photoelectric Effect Theory

In 1887, Hertz discovered electromagnetic waves and determined their speed. In 1889, Hallwachs found

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that a zinc plate produced an electric charge under ultraviolet irradiation. In 1900, Lenard experimentally proved that metals emit electrons under ultraviolet irradiation. In 1905, Einstein proposed the quantum hypothesis to explain the photoelectric effect. In 1916, Millikan verified the quantum hypothesis and measured Planck's constant.

Einstein further provided a quantum explanation for the photoelectric effect: "Energy during the propagation of a ray of light is not continuously distributed over steadily increasing spaces, but it consists of a finite number of energy quanta localized at points in space, moving without dividing and capable of being absorbed or generated only as entities."

Einstein's photoelectric equation:

$$E = h\nu = \phi + K_{max} \tag{1}$$

E = hν represents the energy of a single photon, where: E is the energy of the photon;h is Planck's constant;ν is the frequency of the incident light.

Einstein also won the Nobel Prize in Physics for his work on the photoelectric effect.

2.2 External and Internal Photoelectric Effects

The photoelectric effect is divided into external and internal photoelectric effects. The external photoelectric effect refers to photons exciting electrons from the material surface into a vacuum, forming photoelectrons. The internal photoelectric effect refers to photons exciting electrons from the valence band to the conduction band, generating electron-hole pairs. The "external" in the external photoelectric effect indicates that the bound electron is excited by a photon of a certain frequency and then jumps out of the metal to become a photon, which is a description of the final position of an excited electron. The more specific manifestation of the internal photoelectric effect is that when light shines on an object, there is a change in the conductivity of the object, or a change in the electromotive force.

2.3 Infrared Remote Sensing Technology

Infrared radiation is electromagnetic waves with wavelengths between visible light and microwaves. All objects with temperatures above absolute zero emit infrared radiation. Infrared remote sensing technology utilizes this self-emitted or reflected infrared radiation to detect and identify targets. Infrared remote sensing technology mainly consists of the following components:

Infrared Sensor: Commonly used to detect infrared radiation and convert it into detectable electrical signals. Optical System: Includes lenses and mirrors to focus infrared radiation onto the sensor.Cooling System: Cools the sensor to low temperatures to reduce thermal noise interference in data acquisition.Data Processing System: Processes and analyzes the data received by the sensor, generating usable images and information.

3 APPLICATION OF PHOTOELECTRIC EFFECT IN INFRARED REMOTE SENSING TECHNOLOGY

3.1 Infrared Detectors

Infrared detectors utilize the internal photoelectric effect to excite photons and convert them into detectable electrical signals, characterized by fast response speed and high sensitivity. When infrared photons are incident on optoelectronic materials, photons with energies greater than the band gap are absorbed, causing electrons to jump from valence bands to conduction bands, resulting in electron-hole pairs. The resulting electron-hole pairs are separated by an applied electric field, and the electrons move to the positive electrode and the holes move to the negative electrode, forming a photocurrent. The magnitude of the photocurrent is proportional to the intensity of the incident light, and the infrared signal can be detected by measuring the photocurrent. Currently, widely recognized and extensively used infrared detectors include HgCdTe detectors, InSb detectors, and quantum well infrared detectors.

HgCdTe detectors have high photon absorption rates across the entire infrared spectrum and the lowest dark current due to thermally excited carriers at the same temperature, making them the most important infrared detector material to date. However, the detection performance of all photonic detectors is limited by the internal thermal excitation noise and the external background radiated noise. (Zeng,2012) The research and development direction of cooled infrared detectors of the French company Sofradir is in the leading position in the world. In 2012, Sofradir fabricated a 640×512 longwave red detector with a pixel spacing of 15 m. At 90 K, the detector's Noise-Equivalent Temperature Difference (NETD) can reach 13 mK.(Qi,Feng,Chen,Ning,Liu,Sun&Kang,2022)

InSb detectors, made from III-V semiconductor materials, offer good stability, with performance unaffected by operating and storage time (Mu, 2023). They have higher absorption coefficients and sensitivity in the 3μm-5μm MWIR range and can respond quickly, making them very suitable for military applications such as night vision imaging, target tracking, and precision guidance(Zhang, 2024). Hu et al. (2022) designed a high-frame-rate mid-wave indium antimonide infrared detector system, which achieved 640×512 resolution image output at 200 Hz frame rate, significantly improved the infrared image uniformity and target tracking accuracy, and demonstrated its excellent performance in high-speed target detection and recognition.

The main body of the quantum well infrared detector adopts an n-i-n longitudinal layered structure, and the narrow bandgap material (such as GaAs) is sandwiched between the wide bandgap material (such as AlGaAs) to form a potential well, which restricts the movement of electrons in the vertical direction and quantizes their energy. In this design, the photons of the incident light are absorbed by the electrons in the quantum wells as they enter multiple quantum well nanocomposite layers, and the electrons transition from the ground state to the excited state. The transition electrons are at a higher energy level in the potential well and become free carriers. Under the action of the external electric field, the electron or thermal emission in the excited state tunnels from the quantum well to the conduction band, forming a photocurrent, and finally realizes the detection of infrared light by the detector. This unique subband transition method gives quantum well infrared detectors uniform performance, low cost, and good room-temperature operation, showing great development potential(Liu, Dong & Lv, 2019).

3.2 Thermal Imaging Technology

Thermal imaging technology is an important application of infrared remote sensing, utilizing the photoelectric effect to convert infrared radiation from target objects into visible images. Infrared thermal cameras can capture 8μm-14μm infrared radiation emitted by objects and convert it into visible images based on temperature and emissivity differences. These converted thermal images correspond to the surface temperature distribution of the objects. Currently, thermal imaging technology is widely used in medical diagnosis, military reconnaissance, and fire rescue, providing human eyes with a view of the infrared spectrum and enhancing system observation sensitivity, allowing people to obtain information about the objective world and thermal motion(You,2020).

3.3 Spectral Analysis

Spectral analysis is another important application field of infrared remote sensing technology. Different materials have unique spectral characteristics due to their different emission and absorption properties of infrared radiation. By analyzing these characteristic infrared spectra, we can identify the material composition and structure of target objects. The photoelectric effect plays a crucial role in this process by converting infrared radiation of different wavelengths into different electrical signals, providing the basis for researchers to obtain data for spectral analysis. Infrared spectral analysis is currently widely used in environmental monitoring, mineral exploration, agriculture, and other fields. For example, remote sensing spectral analysis of grasslands can achieve grassland type classification, forage assessment, and monitoring of grassland degradation.

4 THE SHORTCOMINGS AND DEVELOPMENT OF THE APPLICATION OF THE PHOTOELECTRIC EFFECT

Infrared remote sensing technology has been widely used in many fields, but it still has many imperfections and immaturity

4.1 Spatial Resolution Limitations

The spatial resolution of infrared remote sensing, especially thermal infrared remote sensing, is generally lower than that of visible remote sensing. This is because the infrared wavelength is long and the diffraction limit leads to low resolution at the same aperture, which makes it difficult to identify small targets (such as building details, small vehicles), and relies on multi-source data fusion in fine mapping or target recognition.

4.2 Susceptible to Atmospheric Interference

Atmospheric absorption and scattering have a great influence on infrared remote sensing, and gases such as water vapor and carbon dioxide have strong absorption of specific infrared bands (such as 3-5 μm, 8-14 μm), resulting in signal attenuation. At the same time, infrared remote sensing also depends on the weather, and clouds and haze will block infrared radiation, especially in the long-wave infrared band, and the data quality will be significantly reduced in rainy weather.

4.3 The Complexity of the Temperature-Radiation Relationship

The emissivity difference is one of the important factors affecting infrared remote sensing. the emissivity of surface materials (such as metals, vegetation, and water bodies) is very different, and the radiation signals are different at the same temperature, which needs to be accurately calibrated to avoid misjudgment. The problem of mixing pixels also affects the imaging of infrared remote sensing, which can be difficult to interpret when the pixels contain objects of different temperatures/materials (e.g., areas with mixed buildings and vegetation in the urban heat island effect).

For example, multispectral thermal infrared remote sensing has been studied for nearly 50 years, but due to the small number of channels of multispectral sensors, the corresponding weight function is wide, and the vertical resolution is low, and its observation data is greatly affected by the surface temperature and emissivity, atmospheric temperature and humidity profile, etc., which makes it difficult to obtain satisfactory accuracy of the results of multispectral thermal infrared remote sensing inversion under specific conditions such as high atmospheric water vapor content and unknown emissivity (Li et al., 2013; Li et al., 2016)

Although infrared remote sensing technology is still facing many technical problems, with the development and progress of science and technology, scientific researchers are combining the most advanced science and technology to continuously improve and perfect infrared remote sensing technology, making it more mature and more convenient to serve the scientific research and application needs of various fields

1. With the continuous advancement of nanomaterial technology, the emergence of new photoelectric materials brings new opportunities for the application of the photoelectric effect in infrared remote sensing technology. Graphene, as a new two-dimensional material, shows great potential in the field of infrared remote sensing. Its wide-spectrum absorption characteristics, high carrier mobility, and tunable bandgap structure make it an ideal material for infrared detection.

2. Quantum Dot Infrared Detectors (QDIP) represent another important development direction. Quantum dot infrared detectors are similar in structure and principle to quantum well infrared detectors (QWIP): electrons emitted from the emitter are captured by quantum dots or drift to the collector. When infrared radiation excites electrons, the emitted electrons gather at the collector under an external electric field.

Quantum dot infrared detectors theoretically have longer carrier capture and relaxation times than quantum well infrared detectors, resulting in lower dark current and higher photoresponse. Additionally, QDIPs are sensitive to vertically incident light, have effective carrier changes, and can operate for extended periods at high temperatures (Song,2013). The introduction of a sub-point absorber layer can improve the absorption efficiency of the device for near-red light, thereby improving the performance of the device. Under the excitation of 808 nm wavelength, the response of the device increased from 7.62 m A/W to 19.9 m A/W without bias, and the specific detection rate was achievable 4.86×10^{10}cm·$Hz^{\frac{1}{2}}\cdot W^{-1}$.(Qu,2023)

3. The application of artificial intelligence technology in remote sensing is also becoming increasingly widespread. Super-resolution image reconstruction, target recognition, and classification can be achieved through deep learning algorithms combined with artificial intelligence technology, significantly improving the data processing efficiency and intelligence level of infrared remote sensing systems. This holds the promise of developing more capable, efficient, and accurate infrared remote sensing systems in the future.

5 CONCLUSION

As the foundation of infrared remote sensing technology, the photoelectric effect plays a significant role in infrared detectors, thermal imaging systems, and spectral analysis. With the research on new photoelectric materials such as graphene and black phosphorus, and the development of quantum dot technology and artificial intelligence, the application of the photoelectric effect in infrared remote sensing technology will further expand. The integration of the photoelectric effect with emerging technologies is expected to bring dramatic chemical reactions in the field of infrared remote sensing, pushing the technology towards higher resolution, higher sensitivity, and greater intelligence, and bringing more innovative applications to military, medical, agricultural, and geological fields.

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