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CLASSIFICATION SYSTEM OF MODERN OPTOELECTRONIC PRINCIPLES

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Abstract

Optoelectronics is one of the fastest-growing fields within electronics, and specifically within functional electronics. The development of new semiconductor materials and the new optoelectronic elements based on them has expanded the capabilities for optical signal processing. These capabilities have advanced across both primary applications of light energy and information through the creation of new light sources and photovoltaic converters, as well as discrete and integrated optoelectronic components that convert light into electrical signals.

Ongoing research in optoelectronics necessitates an increasingly in-depth description of the optoelectronic principles and effects occurring in solid-state materials. This fosters a better understanding and dissemination of these physical effects, while also enabling the development of new sensors and devices with enhanced performance characteristics. This paper presents a classification of the optoelectronic principles employed in modern optoelectronics and sensor technology. The proposed classification is unique, as no similar scheme is known to exist in literature.

This publication is dedicated to Prof. Ivan Stanchev Kolev, D.Sc. (Eng.) (1949–2016), a distinguished scientist in the field of optoelectronics.

Keywords: Optoelectronic principles; Classification; Physical phenomena; Information conversion

INTRODUCTION

The operation of modern electronic circuits incorporating optoelectronic converters enables the realization of new sensor modules [2-4] and electronic devices [5, 6]. The operating principles of these devices are based on the conversion of light into an electrical signal and vice versa.

Knowledge and understanding of the nature of optoelectronic converters and, by extension, optoelectronic principles enable the effective development of both new semiconductor materials for optoelectronic components and new devices based on novel optoelectronic sensors [2-4, 11, 12].

The physical principles employed in various optoelectronic components to convert light and electrical signals are described in the literature [1, 3, 6, 10, 12, 16]. However, existing descriptions tend to focus on only one or two groups of devices with similar operating mechanisms. This necessitates the creation of a generalized classification system to organize and describe the various distinct physical principles and the relationships between them, thereby facilitating their understanding, study, and application.

The aim of this paper is to propose a classification scheme for modern optoelectronic principles that are widely applied in contemporary optoelectronics and sensor technology. To this end, a review of key literature on the subject has been conducted [1-21].

This paper is based entirely on a theoretical analysis and a literature review designed to enhance understanding of the field under study.

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CLASSIFICATION SYSTEM. DESCRIPTION

Figure 1 shows the classification system for modern optoelectronic principles. Their primary categorization is based on the nature of the optoelectronic effects – specifically, the direction of energy conversion (between electrical and optical energy), the conversion

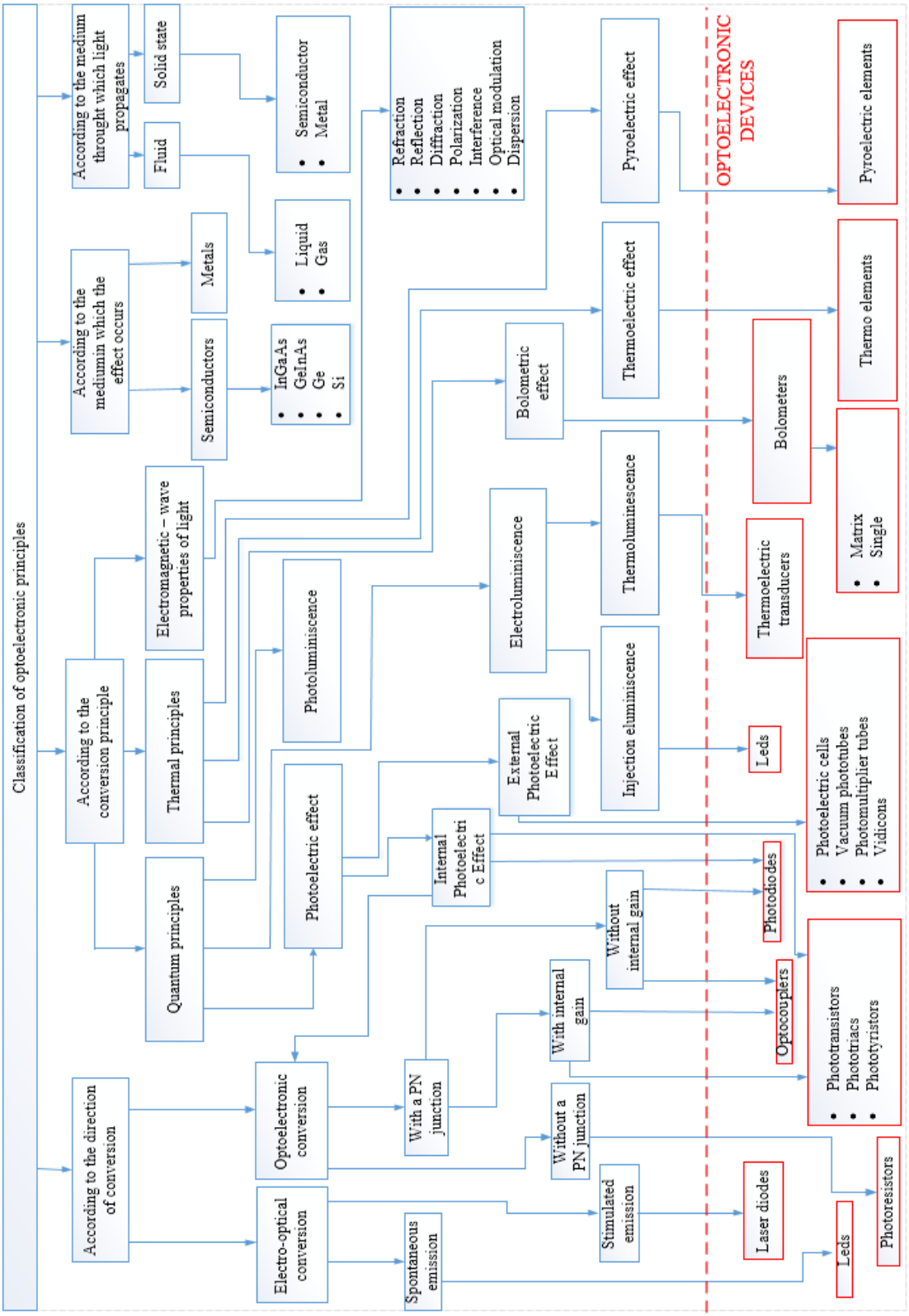


Fig. 1. *Classification system of modern optoelectronic principles.*

principle, and the medium in which light propagates and the optoelectronic principle manifests.

A. ACCORDING TO THE DIRECTION OF TRANSFORMATION

This is the primary criterion for classifying not only optoelectronic effects but also the optoelectronic components based on them. Consequently, they can be categorized as devices that convert electrical energy into light (electro-optical conversion) [9, 17] or light energy into electrical energy (optoelectronic conversion) [2, 13]. These processes are described in detail in [1], while specific applications in sensor technology and optoelectronics are outlined in [2-6]. Research conducted both abroad [19] and domestically [21] demonstrates that a single optoelectronic element – such as a standard LED – can function as both a light source and a light receiver.

During electro-optical conversion, electrical energy is transformed into light energy, with light emission generated in the active region of the optoelectronic device. Depending on the mechanism of light emission, two main types of emission are distinguished: spontaneous and stimulated [8, 9, 15]. Spontaneous emission is characteristic of light-emitting diodes (LEDs) and occurs during the recombination of electrons and holes in the semiconductor material [1]. This process results in light emissions [21].

Stimulated emission is a process in which the amplification of light emission is achieved within the active region of the optoelectronic device. The resulting optical signal is characterized by a narrow spectral range and a high degree of directivity, features typical of the operation of laser diodes [5, 6, 16, 17].

Optoelectronic conversion is a physical process involving the transformation of light energy into an electrical signal. This process relies on the interaction between incident optical radiation and the sensitive region of the optoelectronic component [2, 12]. Depending on the design characteristics of the photosensitive structure [10], optoelectronic conversion is achieved using components with a p-n junction, a p-i-n junction, or no p-n junction [2]. In the latter case, the effect of light manifests as a change in the material's electrical resistance resulting from the generation of minority charge carriers [1, 2], a phenomenon characteristic of photoresistors. Where a p-n junction is present, the absorption of optical radiation alters the electrical characteristics of the junction region. A distinction is made between optoelectronic components without internal amplification, such as photodiodes, and those with internal amplification, such as phototransistors, photothyristors, and phototriacs [2, 11].

Optocouplers are manufactured based on the two types of optoelectronic conversions (light receivers and light emitters) [1, 6].

B. ACCORDING TO THE PRINCIPLE OF CONVERSION

The classification of optoelectronic principles based on the conversion mechanism relies on the physical processes involved in the interaction between light and matter. This allows for the distinction of the fundamental energy conversion mechanisms in optoelectronic devices [1, 2, 8, 9, 12, 15]. This classification distinguishes between quantum principles, thermal principles, and principles related to the electromagnetic wave properties of light [2-4, 15].

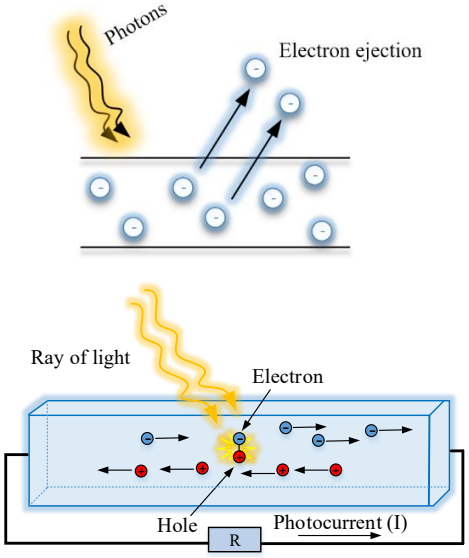


Fig. 2. *External (a) and internal (b) photoelectric effect*

Quantum principles in optoelectronics are based on discrete energy exchange during the interaction between light and matter. They encompass photon absorption and emission processes that trigger electrical or optical phenomena within the active medium. The photoelectric effect, well described in [2], is one such quantum principle; in this process, the energy of incident optical radiation causes the release of electrons, thereby altering the material's electrical state. Depending on the underlying mechanism, a distinction is made between the internal and external photoelectric effects.

The external photoelectric effect (Fig. 2a) involves the emission (ejection) of electrons from the surface of a material upon irradiation with light of a specific spectrum and energy. This effect is utilized in photoelectric cells, vacuum phototubes, photomultipliers, vidicons, etc. [2-4, 5, 6, 7, 12, 14, 19].

The internal photoelectric effect (Fig. 2b) is primarily observed in semiconductor materials and determines the operating principle of a few optoelectronic components [18, 20, 21]. It involves the generation of electron-hole pairs within the material, leading to an increase in its electrical conductivity [1].

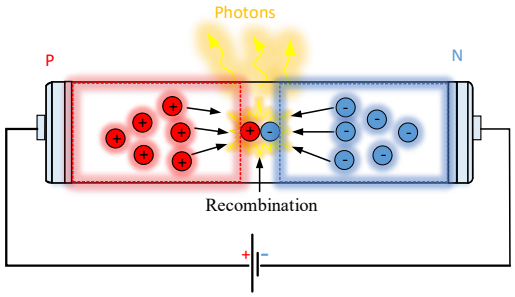


Fig. 3. *Electroluminescence*

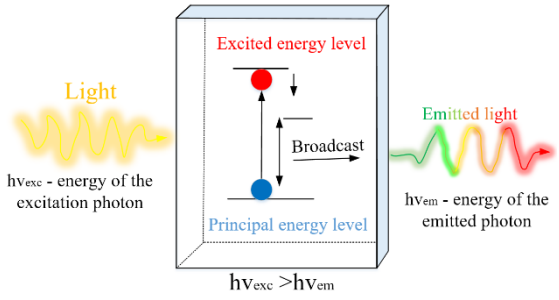


Fig. 4. *Photoluminescence*

Electroluminescence is also among the quantum principles (Fig. 3). Here, an applied electric field or a flowing electric current induces optical emission from the active medium of the semiconductor crystal. This mechanism is characteristic of light-emitting diodes and semiconductor lasers [5, 6]. In these devices, light generation results from electronic transitions within the material [16].

Photoluminescence (Fig. 4) also falls under quantum principles. It occurs upon excitation of the active medium via optical radiation. The absorbed energy is converted and subsequently emitted as light, the spectral characteristics of which depend on the material's properties [1, 2-6, 10, 12, 18].

Thermal principles in optoelectronics utilize the conversion of absorbed optical radiation into the thermal region of the spectrum. This leads to a change in the material's temperature. Consequently, these temperature changes alter the material's electrical characteristics, enabling the conversion of the optical signal into an electrical one based on the spectral composition of the radiation [1-6, 9, 17].

Among the thermal principles, the bolometric effect (Fig. 5) is important. In this process, the energy of incident optical radiation raises the temperature of the sensing element and alters its electrical resistance [2]. Bolometers – implemented either as single sensing elements or as matrix structures [2] for the spatial detection of radiation – operate on this principle.

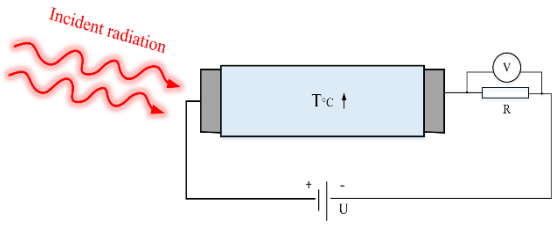


Fig. 5. *Bolometric effect*

The pyroelectric effect also falls under thermal principles (Fig. 6). In this case, a change in temperature over time induces a change in the material's electric polarization [2, 18]. This effect is utilized in pyroelectric

elements [5] to detect the intensity of incident radiation and is particularly suitable for modulated and optical pulse signals.

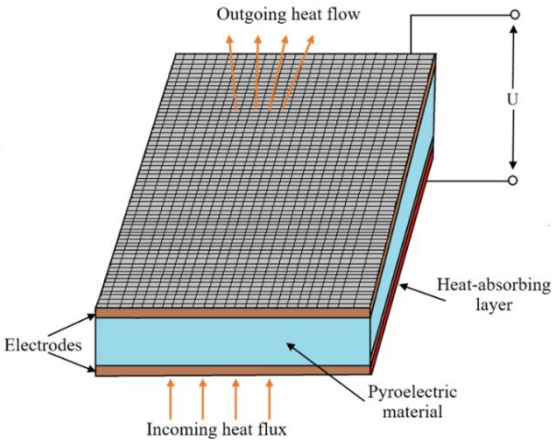


Fig. 6. *Pyroelectric principle*

C. ACCORDING TO THE OPTICAL MEDIUM IN WHICH THE EFFECT APPEARS

Classification based on the medium in which the effect manifests is determined by the physical properties of the material where the interaction between light and matter takes place. The type of optical medium directly influences the nature of the resulting phenomena, the conversion efficiency, and the application scope of the relevant optoelectronic principles. Semiconductor materials play a significant role in this classification. In these materials, the interaction of optical radiation with the material's electronic structure gives rise to various optoelectronic effects. Examples include Silicon (Si) and Germanium (Ge), as well as III-V compounds such as Gallium-Arsenide (GaAs) and Indium-Gallium-Arsenide (InGaAs). These materials differ in their energy structure and spectral sensitivity [2], which determines their suitability for sensors with varying spectral response characteristics [2-6].

In addition to semiconductors, optoelectronic effects also occur in metals. In these materials, the interaction with light is determined by the behavior of free electrons. The resulting surface electromagnetic phenomena find application in specialized optoelectronic and sensor devices [2-6].

D. ACCORDING TO THE OPTICAL MEDIUM IN WHICH LIGHT PROPAGATES

In this classification, the optical medium is regarded as a primary factor governing the operation of a given optoelectronic principle. The physical properties of the optical medium are directly linked to the propagation and transmission of the optical signal. Both solid and fluid (gaseous) media are known, as are transparent and opaque ones [7]. For both groups, it is crucial to consider not only the light spectrum but also the energy carried by the light. Thus, classification based on the medium of light propagation complements other classification categories, ensuring a comprehensive systematization of the physical principles and the practical implementation of optoelectronic components [1–6].

CONCLUSION

The report proposes and describes a classification system for modern optoelectronic principles. This system enables the identification of essential physical relationships between the various groups and fosters a more comprehensive understanding of their application in modern optoelectronics and sensor technology. The presented classification can be used both for analyzing and comparing different optoelectronic principles and for selecting the appropriate principle for a specific sensor application. Establishing such a classification offers not only scientific and research value but also practical engineering utility, contributing to the advancement of knowledge in the fields of optoelectronics and sensor technology.

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