Proceedings of CONF-MSS 2026 Syposium: Mechanical Control and Automation
DOI: 10.54254/2755-2721/2026.BJ33206

Principles, Typical Applications and Development Prospects of Photoelectric Sensors

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Abstract. The Internet of Things, artificial intelligence and intelligent manufacturing are developing very fast in modern society. For this reason, photoelectric sensors have become key parts of intelligent sensing systems. The reason is that they have many good features, such as high precision, fast reaction speed, the ability of non-contact measurement and being easy to make into small sizes. This paper gives a systematic introduction to the basic working rules of photoelectric sensors, and these rules are based on the photoelectric effect and PN junction structures. We take three typical products as examples here, which are smartphone ambient light sensors, optical mice and automotive LiDAR. The paper analyzes how these products work, what their application features are and what practical values they have in daily use and industrial production. On this basis, the paper also sums up the good points and the existing weak points of photoelectric sensors. It also finds out the main difficulties that photoelectric sensors are facing in their current development, including the problem of high cost, the poor ability to adapt to different environments and the low resistance to various interferences. Finally, the paper looks into the future development trends of photoelectric sensors. These trends include higher detection precision, stronger intelligent level, higher integration degree, lower power consumption and wider use in fields like automotive production, medical treatment and industrial detection. The study shows that photoelectric sensors will still play an extremely important role in supporting the development of intelligent systems, and they have very broad application prospects in the future.

Keywords: Photoelectric sensors, photoelectric effect, intelligent sensing, ambient light sensor, development prospect

1. Introduction

We are now in a digital age, and in this age the Internet of Things (IoT), artificial intelligence (AI) and intelligent manufacturing are deeply combined with each other. Intelligent sensing technology is a very important bridge connecting the physical world and the digital world in this age. It is also pushing various industries to carry out intelligent transformation and upgrade their development models. Among all these new technologies, photoelectric sensors have obvious advantages because of their special working way which is based on the photoelectric effect. Their advantages include fast reaction speed, high detection accuracy, the way of non-contact measurement and small product

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DOI: 10.54254/2755-2721/2026.BJ33206

size. So they have become necessary core parts in intelligent sensing systems. People use them widely in many key fields, such as consumer electronics, automotive electronics, industrial inspection, healthcare and smart homes. They have greatly changed the ways of production, people's daily life and the development models of different industries.

Semiconductor manufacturing processes, Micro-Electro-Mechanical Systems (MEMS) and the research of new materials are making progress all the time. With these advances, photoelectric sensors are gradually getting over the traditional technical problems that limited their development. They are developing towards the directions of higher precision, stronger intelligence, higher integration, lower power consumption and better flexibility. The range of their application is also becoming wider and wider. They are no longer only used in traditional consumer electronics, but also in high-end fields like automotive production, industrial manufacturing and medical treatment. At present, autonomous driving technology is being commercialized step by step, consumer electronics are being upgraded in an intelligent way, the need for high-precision industrial inspection is growing fast and smart home technologies are used by more and more people. All these things bring an unprecedented market chance for the photoelectric sensor industry. But at the same time, these developments also put forward stricter requirements for photoelectric sensors, including their technical effect, the ability to adapt to different environments and the efficiency of cost control.

This paper makes a full and detailed study on photoelectric sensors. First of all, it explains the basic working rules of the sensors which are based on the photoelectric effect, and it also introduces the PN junction which is the core structural foundation of the sensors. Then it looks into three representative applications of photoelectric sensors—smartphone ambient light sensors, optical mice and LiDAR sensors used in autonomous vehicles. It analyzes how these sensors work, what their technical advantages are and what practical values they have. Next, the paper makes a systematic evaluation of the strengths and limitations of these three applications, and it also finds out the current challenges that people will meet when using photoelectric sensors in real situations. Finally, the paper talks about the future development prospects and the trends of technological evolution of photoelectric sensors in different fields. The content of this paper can provide a useful reference for people who do further technological research, product development and industrial application of photoelectric sensors.

2. Principles of photoelectric sensors

The core working rule of photoelectric sensors is built on the photoelectric effect. To be more specific, when a certain material is shone by light with enough energy, the electrons inside the material will absorb the energy of photons. Then these electrons can get over the binding force from atomic nuclei and become free electrons. In this way, a current signal that can be detected is produced. This whole process mainly includes three key steps. First is the injection of photons. In this step, the incident photons have interactions with the semiconductor sensing material of the sensor. Second is the excitation of electrons. If the energy of photons is equal to or higher than the semiconductor bandgap, the electrons in the valence band will absorb the energy and move to the conduction band, and then they become free electrons. At the same time, positively charged holes are left in the valence band, and these holes form photogenerated carriers, which are also called electron–hole pairs. Third is the separation and collection of charges. The internal electric field from the core structure of the sensor can separate the photogenerated carriers effectively. It can prevent the recombination of electron–hole pairs and guide these carriers to the external circuit. Finally, a stable current that can be measured is produced [1].

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The core structure of a photoelectric sensor is the PN junction. It is formed when a P-type semiconductor and an N-type semiconductor are closely combined together. The P-type semiconductor has a large number of positively charged holes inside, and these holes are produced by impurity doping. The N-type semiconductor has a high concentration of negatively charged free electrons, and these electrons are also introduced through the similar doping process. When the P-type and N-type semiconductors are connected, carrier diffusion will happen across the junction. Electrons will spread from the N region to the P region, and holes will diffuse from the P region to the N region. This diffusion process will make the N region lose electrons and thus become positively charged. The P region will gain electrons and thus become negatively charged. In this way, a built-in electric field that points from the N region to the P region is formed. This electric field can not only stop the further diffusion of carriers, but also build a state of dynamic equilibrium inside the junction. When the PN junction is shone by light, the photogenerated carriers will be separated and driven by the built-in electric field. Electrons will move towards the N region, and holes will move towards the P region. This movement will generate a photovoltage across the PN junction. When an external load is connected to the circuit, electrons will flow through the external circuit and produce an electric current. In this way, the conversion from optical signal to electrical signal is finished [2].

3. Application status of photoelectric sensors

3.1. Smartphone ambient light sensors

Smartphone ambient light sensors are core small photoelectric parts. They are integrated into the front part of portable electronic devices, and their main function is to detect the light intensity in an intelligent way. The technical foundation of these sensors mainly depends on the internal photoelectric effect in semiconductors. Usually, a silicon-based PIN photodiode with high sensitivity is used as the photosensitive element of the sensor. When ambient photons shoot into the depletion region of the photodiode, and their energy is higher than the bandgap of the semiconductor material, electron–hole pairs will be generated. Under the influence of an external bias voltage or the built-in electric field, these carriers can produce a photocurrent that can be measured. The sensor works in a specific spectral range, and people usually use optical filtering to make this range match the human eye's luminous efficiency function. In this range, the photocurrent has a highly linear relationship with the intensity of the incident light. The weak analog current signal will be amplified and adjusted by a transimpedance amplifier with low noise and high precision. Then an integrated analog-to-digital converter will turn this signal into a one-dimensional digital value that stands for the light intensity. This digital signal will be sent to the main control chip or the display management unit of the device in real time. It is transmitted through standard serial communication interfaces like I^2C or SPI. The system has a predefined adaptive brightness control algorithm. Based on this algorithm, it can adjust the backlight brightness or color temperature of the display in a dynamic and smooth way. By doing so, it can make sure that the display output matches the ambient lighting conditions in the best way [3].

This kind of sensor can bring many advantages to the device system from different aspects. From the view of user experience, the continuous and automatic adjustment of the display can greatly reduce the eye strain of users. This strain is usually caused by the sudden changes of ambient illumination or the too big contrast between the display and the surrounding environment. So the sensor can improve the visual comfort of users and make it easier for them to read on the screen continuously. From the view of device performance, the sensor can avoid setting the screen

DOI: 10.54254/2755-2721/2026.BJ33206

brightness to an unnecessarily high level in low-light environments. This can reduce the power consumption of the display module, which is one of the parts that use the most energy in a smartphone. Thus the battery life of the smartphone can be extended. Besides, with the progress of MEMS and semiconductor manufacturing processes, these sensors have an extremely fast reaction speed, and the speed is usually calculated in milliseconds. They also have a very small size. This allows the sensors to be integrated into the smartphone seamlessly, such as near the earpiece or in the narrow bezel area under the display [4].

3.2. Optical mice

The optical mouse is a computer pointing device that is all-solid-state and uses non-contact working way. It has completely taken the place of the ball-based mechanism that was used in early mechanical mice. Its core technology is based on the combination of the light reflection principle and the photoelectric effect. The optical navigation system of the mouse is mainly made up of three key parts. The first one is a light-emitting diode (LED), and it usually emits red or infrared light to be the illumination source. The second one is a microlens assembly, and its job is to focus the emitted light and collect the light that is reflected back. The third one is a special low-resolution CMOS image sensor, and it acts as the unit for photoelectric detection and signal conversion. The light emitted by the LED will shine on the working surface under the mouse at a certain angle. The texture or tiny features on the surface will make the light produce diffuse reflection. After passing through the microlens assembly, the reflected light will form a continuous tiny image of the surface on the CMOS sensor. This CMOS sensor is like an array of photodiodes. Each pixel in the sensor can turn the intensity of the received reflected light into a corresponding electrical charge through the internal photoelectric effect. Then it can output these charges quickly as a sequence of digital grayscale image frames.

These image frames are captured at a very high speed, usually thousands of frames per second. Then they are sent to a special digital signal processor (DSP) that is integrated inside the mouse. The DSP runs an optical flow algorithm. It can calculate the relative direction and distance of the mouse's movement on a two-dimensional surface. It does this by analyzing the displacement vectors that come from the feature changes between two successive image frames. Then the calculated displacement will be coded into a standardized data packet. The packet is sent to the host system through a wired or wireless interface, and in this way the movement of the computer cursor is controlled. This working way is based on optical imaging and digital image correlation, and it has many important advantages. It can make the mouse have high positioning accuracy, and the resolution can reach several thousand dots per inch (DPI). It also gets rid of the mechanical problems of traditional mechanical mice, such as dust accumulation and encoder wear. So the reliability of the mouse is improved a lot. In addition, the optical mouse does not need a special mouse pad to work. It can run stably on most everyday surfaces, and only highly reflective materials like mirrors will make it work abnormally [5].

3.3. Automotive autonomous driving lidar sensors

LiDAR sensors used in automotive autonomous driving are core photoelectric detection devices. They are mainly used for environmental perception and path planning of the car. They provide important hardware support for advanced autonomous driving systems. These systems need to do obstacle detection, distance measurement and scene reconstruction, and the LiDAR sensors are the key to finish these jobs. Their working principle is based on the Time of Flight (ToF) method and

DOI: 10.54254/2755-2721/2026.BJ33206

the mechanism of photoelectric signal conversion. The core system of the LiDAR sensor is composed of three main parts: a laser emission module, an optical receiving module and a signal processing unit. The laser emission module uses a semiconductor laser to generate high-frequency and narrow laser pulses, and then it sends these pulses to the surrounding environment. When these laser pulses hit the surfaces of objects, diffuse reflection will happen. The reflected light is collected and focused by an optical lens assembly, and then the light is directed to a photoelectric detection array. This array is made up of avalanche photodiodes (APDs) or single-photon avalanche diodes (SPADs).

When photons reach the photosensitive surface of the detector, photogenerated carriers are produced through the internal photoelectric effect. Under an applied bias voltage, these carriers will generate pulsed electrical signals. The signal processing unit can measure the time interval between the emission of laser and the reception of echo very precisely. Then it can calculate the distance between the sensor and the target object according to the speed of light. The LiDAR sensor can scan the surrounding environment at a high speed through rotational scanning or phased-array beam steering. In this way, it can quickly build a three-dimensional point cloud that shows the surrounding environment clearly. This point cloud can record the position, shape and motion characteristics of nearby objects accurately. Then the data from the point cloud is sent to the autonomous driving domain controller of the vehicle. It is transmitted through in-vehicle Ethernet or CAN bus. The data is also integrated with the information from cameras and millimeter-wave radar through multi-sensor fusion. This integrated perception framework can provide reliable information for the key driving functions of the car, such as obstacle avoidance, lane keeping and automated parking [6].

LiDAR sensors have many obvious technical advantages when they are used in autonomous driving. Compared with cameras, they are less affected by the ambient lighting conditions. They can keep a stable detection effect under low-light or bad weather conditions, such as nighttime, rainy and foggy days. Compared with millimeter-wave radar, LiDAR has a better angular resolution and higher distance accuracy. It can detect smaller objects like pedestrians and cyclists more precisely. Besides, the development of solid-state LiDAR technology has reduced the size of the sensor and the manufacturing cost a lot. It also gets rid of the mechanically rotating components in traditional LiDAR. This change has improved the system reliability and the operational lifespan of the sensor greatly. So it can support the large-scale commercialization of autonomous driving technology [7].

4. Advantages and disadvantages

4.1. Smartphone ambient light sensors

• The sensor can adjust the backlight brightness and color temperature of the display in a dynamic way according to the intensity of ambient light. It can make sure that the display state matches the human visual perception in the best way. This can reduce the eye strain of users a lot, no matter the lighting condition is bright or dim. It also improves the comfort of human–computer interaction and makes the interaction more continuous. This advantage is especially useful for people who use smartphones for a long time, because they do not need to adjust the display settings by hand frequently anymore.

• The sensor can reduce the unnecessary power consumption of the smartphone effectively. It does this by lowering the screen brightness in low-light environments. The display module is one of the parts that use the most energy in a smartphone, so this optimization can cut down the overall power consumption of the device. Then the battery life is extended, which makes the smartphone

DOI: 10.54254/2755-2721/2026.BJ33206

more convenient to use in daily life and meets the endurance requirements of portable electronic devices.

• With the help of mature MEMS and semiconductor manufacturing technologies, the sensor has a reaction speed calculated in milliseconds and a very small size. This allows the sensor to be integrated into narrow spaces of the smartphone seamlessly, such as near the earpiece or in the display bezel. It will not make the device bigger, and it also will not affect the industrial design and the portability of the smartphone [4].

• In some mid-range and low-end smartphones, the optical filter of the sensor does not have high enough accuracy. This makes the sensor unable to match the human eye's luminous efficiency function very well. In complex spectral environments, such as places with neon lighting, this problem will make the brightness adjustment of the screen inaccurate or even cause the screen to flicker. These situations will have a bad influence on the user's visual experience [3].

• The sensor needs to use serial communication interfaces like I^2C or SPI to transmit signals. When the bus is used at a high rate, the transmission of signals may be delayed. This delay will cause the brightness adjustment of the screen to lag behind the change of ambient light. As a result, the system cannot respond quickly to the sudden changes of ambient lighting, which makes the adjustment less sensitive and reduces the overall working effect of the sensor.

4.2. Optical mice

• The optical mouse uses a non-contact working way, and this way is based on the light reflection principle and the photoelectric effect. It gets rid of the ball-and-encoder structure that was used in traditional mechanical mice. This new design avoids the mechanical problems of traditional mice from the root, such as dust accumulation and component wear. It improves the durability, operational stability and long-term reliability of the mouse a lot, and it also reduces the need for daily maintenance of the mouse.

• The optical mouse has a high positioning accuracy, and its resolution can reach several thousand DPI. It can detect the small displacement of the mouse accurately and output the displacement vector data stably. This high accuracy can meet the needs of applications that require precise cursor control, such as game playing and graphic design. The optical mouse works much smoother and more reliably than traditional mechanical mice in these applications.

• The optical mouse does not need a special mouse pad, and it can work stably on most common surfaces, including paper, wooden desks and fabric. Only highly reflective surfaces like mirrors will limit its working performance. This wide compatibility with different surfaces makes the optical mouse more useful and flexible. It also brings more convenience for users to use the mouse in different working environments [5].

• In environments with strong direct light, such as strong sunlight shining on the working surface, the external light will interfere with the CMOS sensor. The sensor cannot capture the reflected surface features accurately under this interference. This will cause errors in the analysis of image frames, and then the cursor will drift on the screen, the positioning accuracy will drop and the overall working performance of the mouse will become worse.

4.3. Automotive autonomous driving lidar sensors

• LiDAR can realize the three-dimensional perception of the surrounding environment, and it is based on the Time of Flight (ToF) principle. It does not rely on the ambient lighting conditions at all. It can keep a stable detection performance under bad environmental conditions, such as nighttime,

DOI: 10.54254/2755-2721/2026.BJ33206

heavy rain, thick fog and dusty air. This ability allows the autonomous driving system to identify the position, shape and spatial distribution of obstacles accurately. So LiDAR can provide reliable all-weather perception support for autonomous driving systems.

• LiDAR has an extremely high angular resolution and high distance measurement accuracy. Compared with millimeter-wave radar, it can distinguish small objects like pedestrians, cyclists and other small obstacles more precisely. This can reduce the possibility of missing detections and making wrong judgments a lot, and thus it improves the reliability and safety of the decision-making systems of autonomous driving [6].

• Solid-state LiDAR does not have the mechanically rotating components that are used in traditional LiDAR systems. This makes its structure more compact, and it also has a better ability to resist vibration and mechanical stress. So the solid-state LiDAR can be integrated into different positions of the vehicle body flexibly. It also reduces the risk of mechanical failure and extends the operational lifespan of the sensor. All these features make it very suitable for the harsh working conditions of automotive environments [7].

• The cost of LiDAR is still relatively high, especially for the high-resolution LiDAR systems that are used in the automotive industry. The high unit cost of LiDAR increases the overall production cost of autonomous vehicles. This becomes a big obstacle for the large-scale use and widespread commercialization of autonomous vehicles.

• Under extremely bad weather conditions, such as heavy rain or thick fog, the laser beams of LiDAR will be scattered or absorbed by water droplets and small particles in the air. This effect will reduce the detection range of LiDAR and make the density of the point cloud lower. Thus it limits the accuracy of detecting distant objects, and it may even create blind spots in the environmental perception of the autonomous driving system [7].

5. Conclusion

As a core part of intelligent sensing systems, photoelectric sensors use the basic principle of the photoelectric effect to work. They also have many advantages like fast reaction speed, high detection accuracy and non-contact measurement. For these reasons, they are used widely in many fields, such as consumer electronics, automotive electronics, industrial testing, smart homes and healthcare. They have become an essential part in supporting the development of industries like the Internet of Things, artificial intelligence and intelligent manufacturing. Typical photoelectric sensor products, including smartphone ambient light sensors and optical mice, show people the good ability of photoelectric sensors in miniaturization and integration. They also prove the core value of these sensors in improving user experience, optimizing device performance and reducing maintenance costs. At present, the development of photoelectric sensor technology is facing some challenges. These challenges include the limited accuracy of optical filters, the delay of signal transmission, the monopoly of high-end core technologies by a few enterprises and the poor ability to adapt to extreme environments. But with the continuous combination of semiconductor manufacturing, MEMS technology, artificial intelligence and new materials, photoelectric sensors are developing towards the directions of higher precision, stronger intelligence, higher integration, miniaturization, lower power consumption and better flexibility. They are gradually getting over these technical bottlenecks that limit their development [8].

In the future, the application range of photoelectric sensors will keep expanding. They will not only be used in traditional consumer electronics, but also in more and more high-end fields like automotive production, industrial manufacturing, medical treatment and the Internet of Things. They will remain the core parts of intelligent sensing systems in different fields for a long time. Many

DOI: 10.54254/2755-2721/2026.BJ33206

trends in the market will bring great market chances for the photoelectric sensor industry, such as the intelligent upgrading of consumer electronics, the fast development of autonomous driving, the growing need for high-precision industrial testing and the comprehensive perception of smart homes. Among all these fields, automotive electronics and healthcare will become the sectors with the fastest growth speed [9]. At the same time, the global market for photoelectric sensors is still expanding, the process of domestic substitution of photoelectric sensors is speeding up in many countries and the competitiveness of local enterprises is improving steadily. These enterprises are doing well in core technology development and industrial application, and they bring new development power to the photoelectric sensor industry. From the technical point of view, photoelectric sensors are changing from simple "data collection devices" to "intelligent sensing units". The key development directions of the sensors include the intelligent processing on the edge side, the fusion of multi-sensors and the application of advanced new materials. These technological innovations will not only improve the detection accuracy and reaction speed of photoelectric sensors, but also promote the deeper combination of photoelectric sensors with technologies like artificial intelligence and the Internet of Things. In the end, these innovations will help people make sensing systems that are more intelligent, more efficient and more precise.

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