Creation of an optical sensor based on the pCdTe – nCdS and pCdTe – nCdSe heterostructure for detecting polluted air

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Abstract: This article discusses the creation of optical sensors for detecting polluted air based on the pCdTe – nCdS and pCdTe – nCdSe heterostructures. It was established that the developed optical sensors, with an automatic control system using Arduino, operate effectively across wide ranges of the infrared (IR) spectrum. The study found that the increased responsiveness of the optical sensor ensures uniform sensitivity and a high degree of background light suppression. It was demonstrated that using the optical sensor, it is possible to determine the level of dust and smoke in both indoor environments and open land areas.

1 Introduction

Optical sensors with a new heterostructure photodetector based on pCdTe – nCdS and pCdTe – nCdSe for determining air pollution with an automatic control system using Arduino designed for supply and exhaust air ventilation (particle fixation area 1 m^2) [1]. The largest source of aerosol emissions into the atmosphere are workshops using coke ovens. Metallurgical plants, cement and brick factories install electric precipitators, and dust detectors are used to monitor the contamination of these filters [2]. For efficient operation of the sensor, it is necessary to deeply study the optical properties of the heterostructure photodetector, which is considered the main element of the sensor.

The optical properties of the heterostructure showed that the absorption spectra of cadmium telluride doped with the first group of elements shifts to a longer wavelength region up to 0.6 eV of the spectrum and this gives grounds that the photovoltage appears in the impurity absorption region [3].

If a semiconductor crystal is illuminated with light at such a frequency that the photon energy is equal to or greater than the energy gap of the semiconductor [4], the incident photons have sufficient energy to excite electron-hole pairs, which increase the conductivity of the crystal [5]. This increase in conductivity is a function of light intensity and increases with increasing intensity as a photon is absorbed for each electron-hole pair created [6].

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In this regard, in this work, the optical parameters of the created sensors based on a heterostructure for determining air pollution were investigated.

2 Research methodology

To create an optical sensor with a new heterostructure photodetector, the working chamber described in the work was used [7]. In the working chamber setup (VUP-4), a vacuum level of about 10^{-4}–10^{-5} mm Hg was achieved, where the deposition of the initial semiconductor material and impurities took place. In the working vacuum chamber, a holder designed as a frame was located 20-25 cm from the bottom, on which substrates were attached. The distance between the frame and the crucible was within 5.5-7.5 cm. By rotating the holder, the deposition angle could be varied from 0 to 90 degrees [8]. The substrate temperature was maintained using a heater fitted over a quartz cap. This heater allowed changing the substrate temperature using chromel-alumel thermocouples. Tungsten or molybdenum wire crucibles with a diameter of 0.6 mm, shaped into a conical basket with a surface area of 60 mm^2, were used for evaporating the semiconductor material CdTe and impurities. An aqueous suspension of beryllium oxide or aluminum oxide was applied to the surface of the basket [9].

For CdTe films, elements from the first group, silver and copper, were chosen as doping impurities. The selection of these metals as impurities is due to the following reasons. Firstly, the optimal diffusion (doping) temperature of silver and copper in CdTe is relatively low and lies within the substrate temperature range of 80 to 300°C [10], which allows for obtaining CdTe films with the highest photoconductivity and stable characteristics. Secondly, these impurities are necessary to neutralize surface states and influence the barrier between crystallites [11]. It can be assumed that intercrystalline barriers are optimized without reducing the maximum photoconductivity value, and the crystallite size is also optimized. The deposition time t, thickness d, and deposition rate vk of CdTe were experimentally determined to achieve the best heterostructure: $t \approx 15 \div 20\,\mathrm{min}$ v_k = 1.5 nm/s, d = 1 μm [12]. The condensation rate of CdTe, determined by the ratio of film thickness to deposition time, provides high-quality semiconductor film devices for further use [13].

Measurements of the spectral dependencies of photoconductivity (PC) and short-circuit current (I_{shc}) were conducted using the methods of steady-state photoconductivity on a setup where the block diagram included a based heterostructures photodetector. The sample placed in a cryostat was illuminated by a globar-type lamp through an IKS-14 monochromator [14]. To reduce the influence of scattered light (when measuring in the IR range), silicon and germanium filters were used. Signal registration was carried out by an electrometer ED-05M. When connected to a load resistance closing the sample, the short-circuit current was measured. When an external voltage source was included in the circuit, the total signal, dependent on both photoconductivity and photo-EMF, was measured [15]. Conducting measurements when the source was turned on at opposite voltages showed that the difference in signals is proportional to the photo-EMF, and the sum is proportional to the photoconductivity. The results obtained show that the photodetector of the optical sensor meets the requirements for sensors for air pollution detection and can be used in automatic ventilation systems with Arduino applications.

3 Experimental results and their discussion

The proposed optical sensors for detecting air pollution contain a base with a central through hole on the lower and upper surfaces. Inside the sensor, where polluted air particles pass through, an IR LED is placed. The emitted rays from the LED pass through lenses and hit the surface of the polluted air particles, while the rays that do not hit the particles are reflected by a mirror located inside the opposite wall of the sensor. Thus, the rays emitted by the IR LED maximally hit the polluted air particles, and the rays reflected by the particles pass through lenses to the photodetector based on the heterostructure.

In the absence of air pollution, the light emission from the source directly hits the photodetector through the reflecting mirror, while the background light is "extinguished" in the reflecting cells, which act as "traps" for light. In these cells, almost complete suppression of the "parasitic" signal from the IR LED and incoming external light occurs.

When air pollution occurs, it freely penetrates the inner space of the sensor through straight guiding channels and a slit gap. The radiation from the light source, scattered by the polluted air particles, is registered by the photodetector. This ensures high response speed and uniform sensitivity of the sensor regardless of the direction of the polluted air flow.

The method of manufacturing a semiconductor sensor with a new heterostructure photodetector for detecting air pollution is as follows: the semiconductor sensor is made from plastic material for the body, with a metal cover for electromagnetic field protection. Inside the body, there are semiconductor elements, a block diagram for controlling the IR LED, an amplifier circuit, and a glass mirror for reflecting the IR beam. The optical sensor is small in size, weighing 17 grams, which has been reduced from the prototype weight by using new parts such as a reflective mirror and a photodetector with a new heterojunction, making it suitable for installation in hard-to-reach places.

Figure 1 shows the block diagram of the sensor with a new heterostructure photodetector for detecting air pollution, which helps to easily understand the important components of the sensor circuit.

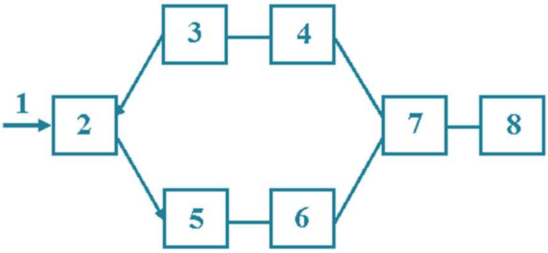

Fig. 1. Block diagram of a sensor with a new heterostructure photodetector: 1-source of contaminated air, 2-working chamber, 3-infrared LED, 4-LED controller, 5-heterostructure photodetector based on p CdTe – n CdS and p CdTe – n CdSe, 6-op signal amplifier, 7-microcontroller Arduino platform, 8-monitor or computer.

The sensor's housing and circuit are from the existing prototype model GP2Y1014AU0F. Inside the working area of the sensor, four main components are located: the infrared light-emitting diode (LED), the photodetector (replaced by the new heterostructure photodetector), the reflecting mirror (first used in this sensor), and a pair of lenses. The LED and the photodetector are positioned within the sensor so that their optical axes intersect within the sensor's detection area with the help of the reflecting mirror. When polluted air enters the sensor's detection area, the light inside the sensor reflects off dust or smoke particles, and the amount of detected light varies depending on the density of the particles. The generated current by the photodetector changes accordingly. The output voltage compared to the density of pollution and smoke particles is shown in Figure 2 [16].

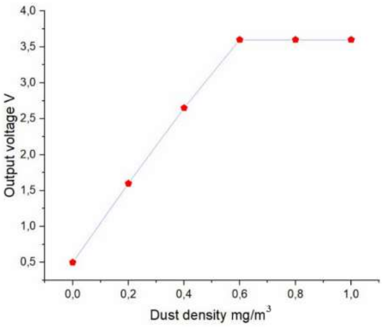

Fig. 2. Output voltage versus particle densit

To work with the sensor, we need only 2 contacts out of 6 sensor contacts. On the first of them we will turn on/off the LED, and on the second we will read the analog signal from the sensor output. Resistor R_1=150Ohm and capacitor C_1=220μF are necessary to generate an LED control pulse. Without these resistor and capacitor, the sensor module will not be able to operate. In order to provide the required signal at the sensor output, it is necessary to apply pulses with a period of 10ms to the LED, and the pulse duration should be no more than 0.32ms. As recommended in the instructions for the sensor prototype, the duration of this pulse should be 0.28ms per sensor.

This device model differs from other prototypes in the following ways:
The opaque partitions in the pollution particles in the intake chamber are made in the form of radially oriented plate ribs, the internal end sections of which are located near the through hole of the base, forming straight through channels for the passage of pollution particles and gas; the smoke intake chamber contains a plate bottom, the area of which corresponds to the area of the through hole in the base , installed under the specified hole at a level corresponding to the level of the lower surfaces of the funnel, with the formation of a slot gap for the penetration of pollution particles and gas, and in the measuring chamber there are elements of a labyrinthine light-reflecting system distributed along the perimeter of the side fence, characterized in that the optical sensors with a new heterostructure photodetector pCdTe – nCdS and pCdTe – nCdSe, for determining pollution particles and gas in the air, containing a base with a central through hole, on the lower and upper surfaces of which a particle smoke intake and measuring chamber are respectively mounted, while the particle smoke intake chamber contains opaque funnels fixed on the lower surface of the base and distributed in the circumferential direction over its area, installed in the circumferential direction with a gap relative to each other so that their outer end sections form an open side surface of the contamination particles of the intake chamber, and their side walls form through channels for passage particles of pollution and gas, the measuring chamber contains a closed side fence fixed on the upper surface of the base, a light source, a photodetector, and an opaque screen that prevents direct radiation from the light source into the photodetector [17].

It differs from the used sensors, which consist only of a silicon photodiode with lenses and an amplifier unit, as follows: new sensors with a heterostructure photodetector for determining pollutant particles in the air, containing a base with a central through hole, on the lower and upper surfaces and inside the sensor where polluted particles pass air there is an IR LED, which, when emitting rays through the lenses, hits the surface of polluted air particles, and which rays that do not reach are reflected by a mirror located inside opposite the wall of the sensor, the rays that are emitted by the IR LED hit the polluted air particles as much as possible. After the rays reflected by particles of polluted air enter through the lenses of a photodetector based on a p CdTe – n CdS and p CdTe – n CdSe heterostructure, with this sensor system the emission line of the IR LED and the line of reception of the rays reflected by the particles are located at an angle of 90˚, which reduces the sticking of polluted air particles to the lenses and to the reflecting mirror.

A sensor with a new heterostructure photodetector for determining pollution in the air using an existing body of the GP2Y1014AU0F brand in the working area, distinguished by the prototype that there are four main components: an infrared light-emitting diode (light source), a photodiode (detector) we replaced with a new heterostructure photodetector, a reflecting mirror which is also the first to be used on this sensor and a pair of lenses.

A sensor for determining air pollution according to the prototype, characterized in that a new heterostructure photodetector is used, which allows it to work more efficiently than a conventional silicon photodiode, that it contains a reflective mirror that reflects 90% of light and increases the flux of infrared radiation of the working area.

Thus, sensors were created based on the heterostructure p CdTe – n CdS and p CdTe – n CdSe, with this sensor system the emission line of the IR LED and the line of reception of rays reflected by particles are located at an angle of 90˚, which reduces the sticking of polluted air particles to the lenses and to the reflecting mirror and they can be used in hard-to-reach places in buildings and in other branches of science.

4 Conclusions

In conclusion, it can be noted that the created sensors based on the CdTe heterostructure have a number of advantages over existing sensors:

1. This heterostructure sensor operates in a wide range of received electromagnetic radiation, extending to the near infrared region of the spectrum (0.4-3.0 μm);
2. Due to the addition of silver impurity, the signal and current power increases.
3. Photosensitivity increases with the addition of silver impurity, which photosensitivity appears in the impurity absorption region

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