Photoconductivity in organic phototransistors and photoresistors based on thin films of polymer materials

Salikhov R.B.
Institute of Physics and Technology, Ufa University of Science and Technology, 450076 Ufa, Russian Federation.

Ostaltsova A.D.
Institute of Physics and Technology, Ufa University of Science and Technology, 450076 Ufa, Russian Federation.

Salikhov T.R.
Institute of Physics and Technology, Ufa University of Science and Technology, 450076 Ufa, Russian Federation.

Balapanov M.Kh.
Institute of Physics and Technology, Ufa University of Science and Technology, 450076 Ufa, Russian Federation., balapanovmk@mail.ru

Kubenova M.M.
Institute of Physics and Technology, L.N. Gumilyov Eurasian National University, 010008 Astana, Kazakhstan Republic.

Follow this and additional works at: https://www.epbys.kz/journal

Part of the Condensed Matter Physics Commons, Electronic Devices and Semiconductor Manufacturing Commons, Engineering Physics Commons, Physical Chemistry Commons, and the Polymer and Organic Materials Commons

Recommended Citation

REVIEW

Photoconductivity in Organic Phototransistors and Photoresistors Based on Thin Films of Polymer Materials

Renat B. Salikhov [a], Anastasia D. Ostaltsova [a], Timur R. Salikhov [a], Malik Kh. Balapanov [a,*], Marzhan M. Kubenova [b]

[a] Institute of Physics and Technology, Ufa University of Science and Technology, 450076 Ufa, Russian Federation
[b] Institute of Physics and Technology, L.N. Gumilyov Eurasian National University, 010008 Astana, the Republic of Kazakhstan

Abstract

Organic phototransistors and photoresistors may become key devices in photonics and optoelectronics in the near future, providing high sensitivity and controllability in response to light signals. Their operating principle is based on the conversion of light energy into electrical signals, which makes them indispensable in various applications, including sensors, solar cells and displays. One of the important aspects of organic photoelectronic devices is high photosensitivity, which determines the ability of the sensor to register even weak light fluxes. Organic phototransistors, as a rule, demonstrate a higher level of photosensitivity compared to classical inorganic analogs due to the improved structure of materials and deposition technology. The analysis of the input and output characteristics of transistors carried out in the work shows that organic photoelectronic devices will be able to provide flexibility in development and settings. These parameters play an important role in determining the efficiency and reliability of devices under various operating conditions. As a result, organic phototransistors and photoresistors will not only expand the capabilities of modern technologies, but also open new horizons for research and development in the field of lighting and communication systems.

Keywords: Photoconductivity, Photosensitivity, Phototransistors, Photoresistors, Photovoltaics

1. Introduction

In today's world, where technology is developing at an incredible speed, we are witnessing significant progress in the field of electronics and photonics. One of the key aspects that determines this progress is the understanding and application of the phenomenon of photoconductivity, as well as the development and use of phototransistors. Photoconductivity is a phenomenon in which materials change their electrical properties in response to light. This property allows the creation of devices that can convert light into an electrical signal, which opens up wide possibilities for application in various fields, including optical communications, medical diagnostics, as well as in the field of solar cells and photodetectors [1−7].

The phenomenon of photoconductivity plays an important role in various fields of science and technology, such as optoelectronics, solar energy and sensors. The study of photoconductivity allows us to better understand the mechanisms of interaction of light with matter and to develop new materials and devices with improved characteristics [8−12].

The relatively low conductivity of semiconductors and insulators can be significantly altered by illumination. From the dependence of photoconductivity on factors such as excitation photon energy, illumination intensity, or ambient temperature, considerable information can be obtained about the distribution of electronic states in a material and about the processes of carrier generation and recombination [13,14].

Photoconductivity measurements have been used to study the electrical and optical properties of materials.

It is a process of increasing electrical conductivity by absorbing photons with energies equal to or greater than the band gap energy of the material [15]. The conductivity of a material is changed by changing the free carrier density and mobility. The rate of electron-hole pairs generation, minority carrier lifetime, and transport mechanism are also important parameters affecting photoconductivity [16—21].

The illuminance of any light source is measured using different types of calibrated equipment available in the market such as spectral radiometer, photometer, lux meter and optical lens based systems. A study [22] evaluated the photoresistor or light dependent resistor (LDR) and phototransistor to see if it is useful for determining the light patterns of halogen and xenon lamps.

The demand for high-performance, low-power visible light photodetectors is critical for their use in numerous industries such as biomedical health monitoring systems, electronic eyes, and advanced lighting systems [23—25].

Phototransistors are semiconductor devices that convert optical signals into electrical signals. They have become an integral part of many modern technologies including lighting systems, optical communications, and photovoltaic devices. Phototransistors operate by changing the conductivity of a material in response to incoming light [26,27].

Unlike conventional transistors that require an electrical signal to control, phototransistors respond to the light intensity, making them ideal for sensing applications. They are widely used in photocells that detect the presence and intensity of light, as well as in cameras and scanners that require high sensitivity to light. Modern phototransistors are made from a variety of semiconductor materials, such as silicon and gallium arsenide, which allows them to achieve a wide range of sensitivities and response times. Their applications range from household appliances to complex industrial systems, making phototransistors an important element in the evolution of electronics and photonics [28,29]. Organic phototransistors represent a unique area of semiconductor technology, with high potential for creating devices with improved characteristics. These components, using organic semiconductors, open up new perspectives in the development of flexible electronics, integrated sensors, and high-efficiency solar cells [30].

The main advantage of organic phototransistors is their ability to efficiently convert light signals into electrical signals. This quality makes them ideal for use in photodetectors, where high sensitivity and response speed are critical. The use of organic materials also allows for the creation of devices with low weight and low production costs.

Despite their obvious advantages, organic phototransistors face a number of challenges, such as stability and durability in environmental conditions. Research in this area is focused on finding new polymers and molecules that can improve the performance of the devices, as well as on developing technologies that help increase their service life [31].

Ultimately, the development of organic phototransistors can lead to the creation of innovative solutions that will be used in various fields, from medicine to consumer electronics [32].

Photoresistors, or light-sensitive resistors, are key components in the world of electronics that can change their resistance depending on the level of illumination. These devices are widely used in a variety of fields, from simple light signals to complex automatic lighting control systems.

The operation of photoresistors is based on the phenomenon of photoconductivity in which materials such as CdS (cadmium sulfide) or Si (silicon) become more electrically conductive due to the absorption of electromagnetic radiation. This property allows photoresistors to be used in various sensors that automatically respond to changes in the environment [33—35].

For example, in street lamps, photoresistors can provide automatic switching on and off of the light depending on the darkness [36]. In addition, they are used in photometric devices, as well as in automation systems where sensitivity to changes in illumination is required [37].

In addition, with the development of technology, photoresistors are becoming more versatile, which allows them to be integrated into various electronic devices, opening up new opportunities for innovation in futuristic design and functionality [38].

Organic photoresistors are advanced devices that convert light signals into electrical signals using organic semiconductors. Their unique structure and properties provide significant advantages over traditional inorganic photoresistors, making them indispensable in modern technologies [39].

Among the main advantages of organic photoresistors are flexibility, lightness, and the possibility of large-format production. This opens up new path for integration into various electronic devices and systems, from portable electronics to complex sensor networks. Organic materials, such as polymer compounds or small molecules, allow high photosensitivity coefficients to be achieved, making them particularly attractive for use in solar cells and optoelectronic systems.

However, despite all the advantages, organic photoresistors still face some challenges, including the need to improve stability and durability. Research in this area is ongoing, and further advances are likely to

change the way we perceive and use photoresistors in the future.

Solar cells, or photovoltaic cells, are one of the most important technologies in the field of renewable energy [40]. They are able to convert solar energy into electrical energy, making them key to solving modern energy problems. Depending on the materials used, solar cells are divided into two main categories: organic and inorganic [41,42].

Organic solar cells made from carbon compounds offer unique advantages such as lightness and flexibility, as well as potentially low manufacturing costs. Their ability to be transparent opens up new horizons for integration into architecture and electronic devices. However, despite their promising prospects, their efficiency and durability remain the subject of active research [43,44]. Although energy conversion efficiencies have exceeded 10 %, low device stability remains a major challenge [45]. On the other hand, inorganic solar cells, most often silicon-based, have gained recognition for their high efficiency and stability. They have become the standard in solar energy, but their production can be less environmentally friendly and more expensive [46,47]. Research into new materials and technologies is ongoing, leading to hybrid solutions that can combine the advantages of both types of solar cells.

In recent decades, the rapid development of organic electronics has led to the emergence of new materials and devices that have the potential to revolutionize the world of optoelectronics. Among them, organic phototransistors (OPTs) and photoresistors (OPRs) occupy a special place, offering unique advantages over traditional inorganic counterparts.

Their distinctive features include:

* Low cost: Organic materials are readily available and inexpensive to produce, making OPTs and OPRs attractive for mass production.
* Flexible and lightweight: Organic materials can be easily processed into thin films, allowing for the creation of flexible and lightweight devices.
* High sensitivity: OPTs and OPRs can exhibit high sensitivity to light, making them ideal for use in a variety of applications such as light sensors, photodetectors, and solar cells.

However, despite these advantages, the development and optimization of OPTs and OPRs is still in its early stages. A number of challenges need to be addressed, such as:

* Low stability: organic materials are susceptible to degradation when exposed to light, moisture, and oxygen, which limits the lifetime of devices.

* Low carrier mobility: organic materials have lower carrier mobility than inorganic materials, which can limit the operating speed of devices.

Despite these challenges, research in the field of organic phototransistors and photoresistors is actively developing. Researchers are working on creating new materials with improved properties, optimizing device architectures, and developing new manufacturing technologies.

This article provides an overview of recent advances in OPTs and OPRs and discusses their application prospects in various fields, such as:

* Sensors: creating light sensors for various applications, including medical, industrial, and environmental.
* Optoelectronics: developing new devices for display, lighting, and communication.
* Energy: creating efficient solar cells.

This article provides an overview of recent advances in organic phototransistors and photoresistors and discusses their potential to revolutionize optoelectronics in the future.

2. Organic materials and nanocomposites

Photoconducting properties of new composite based on the CdSe nanoplatelets and poly [N-9′-heptadecanyl-2,7-carbazole-alt-5,5-(4′,7′-di-2-thienyl-2′,1′,3′ benzothiadiazole) (PCDTBT) have been studied in Ref. [15]. PCDTBT polymer and CdSe/CdS nanoplatelets solutions mixture with ratio 1:3 in chloroform with concentration 10 g/l was deposited on the glass substrate by the spin-coating at 1000 prm. Obtained film was dried in argon (Ar) atmosphere at the temperature of 70 °C for 24 h. Finally, aluminum electrodes were deposited on the film surface in a planar configuration using thermal evaporation in Fig. 1. The distance between the electrodes was 1 mm. A tenfold increase in photoconductivity was found with the addition of nanoplatelets CdSe/CdS.
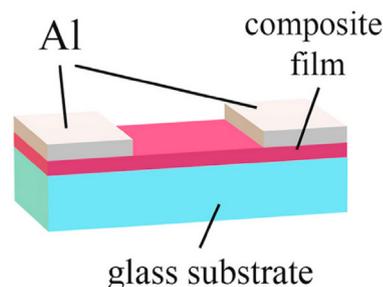

Fig. 1. A scheme of the investigated sample structure [15].

Low-voltage photoswitchable OFETs (organic field-effect transistor) exhibiting two or more stable discrete states characterized by switching ratios less than 1000 are reported in Ref. [26]. The architecture of these devices is shown schematically in Fig. 2. It is known that spirooxazine (SpOx) undergoes photoisomerization to the open zwitterionic form when illuminated in solution with UV or violet light. It is known that spirooxazine (SpOx) undergoes photoisomerization to the open zwitterionic form under illumination in solution with UV or violet light. Back isomerization occurs when the system is illuminated with visible light. Very similar processes might occur also in the photochromic thin films incorporated in the structure of the OFET.

The structure of the FET with a composite active layer based on polyvinylcarbazole (poly (9-vinylcarbazole)—PVK:Ni) is shown in Fig. 3. During the fabrication of the field-effect transistor structures, PVK was dissolved in chloroform, in which a colloidal solution of Ni nanoparticles was also prepared [27].

In Ref. [48] we have discussed the optoelectronic properties of a new poly (2-ethyl-3-methylindole) (MPIn). Samples of photoresistor devices were prepared as follows. A glass substrate with a conductive indium tin oxide (ITO) coating was washed in an ethanol solution and then dried in a muffle furnace for 10 min at 50 °C. A film of MPIn was spin-coated from the solution over the ITO coating. The spin time was 120 s, and the spin speed for three samples was 700, 800, and 900 rpm. In this case, the resulting films had a thickness of 0.7, 0.5, and 0.4 μm, respectively. After that, the samples were placed in a muffle furnace at 70 °C and kept there for half an hour to remove residual solvent. An upper aluminum electrode was deposited over the MPIn by thermal evaporation in a vacuum setup. The electrode had the form of an S-shaped track with a width of 1 mm (Fig. 4a). The thickness of the aluminum electrode was 500 nm.
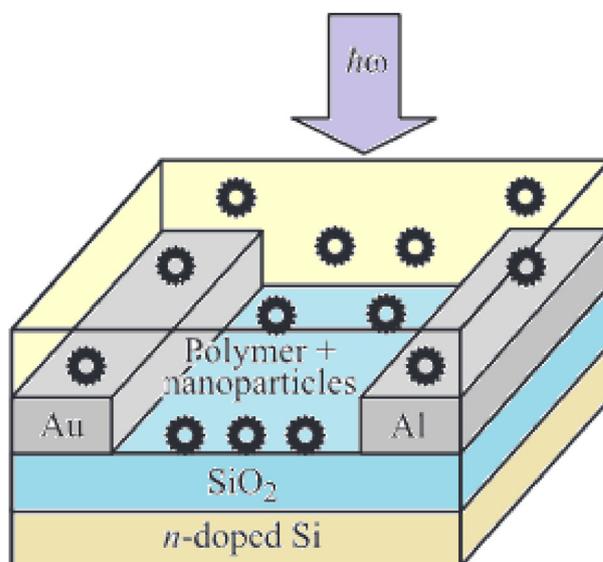

Fig. 3. Structure of a field-effect transistor with a composite active layer based on PVK: Ni [27].
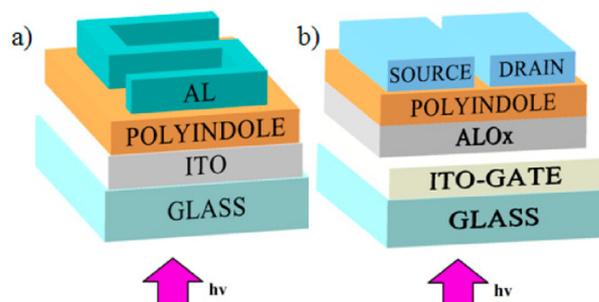

Fig. 4. Structure of (a) photoresistor and (b) phototransistor [48].

Samples of phototransistors based on polyindole films with the structure shown in Fig. 4b were also created. Glass coated with a conducting layer of ITO as a gate was used as a substrate. The polyindole film was created by centrifugation from a solution. The centrifugation parameters were 800 rpm, the rotation time was 2 min. The residual solvent was removed by heating in a muffle furnace for 30 min at a temperature of 70C.

Optically controlled organic field-effect transistors containing a binary mixture of fullerene C60 (n-semiconductor) and spiropyran (photosensitive conductivity modulator) as an active layer were developed and manufactured. Considering the enormous practical interest in photocontrolled OFETs, as well as the above-mentioned technological disadvantages of multilayer transistors (the manufacture of a multilayer device in this case is quite expensive. In addition, the switching efficiency is reduced due to photodegradation of photochromic molecules and the presence of a large number of layers, which makes it difficult for photons

Fig. 2. Architecture of the developed photoswitchable OFET [26].

to reach the photochromic molecule), in this work we set ourselves the goal of manufacturing and evaluating an optically controlled mixed-type OFET containing a binary mixture of fullerene C60 and spiropyran 1 as an active layer (Fig. 5a). For a more objective and rigorous comparison of our results with published data, we also manufactured a multilayer transistor in which fullerene C60 and spiropyran 1 are located in separate layers (Fig. 5b) [49].

In the article [50] the optoelectronic properties of a new polymer, poly (2-(1-methylbut-2-en-1-yl)aniline), with different doping and oxidizing agents are discussed. All polymer samples were prepared as follows: a solution of the oxidizing agent in 50 ml of 0.2 M acid (Table 1) was slowly added to a solution of 1 g (6.2 mmol) of 2-(1-methylbut-2-en-1-yl)aniline in 50 ml of 0.2 M aqueous acid solution (Table 1) at room temperature with continuous stirring. The molar ratio of monomer and oxidizing agent for all samples was 1:1.25.

Structure of a photoresistor with a polyaniline derivative film is shown in Fig. 6. The upper aluminum electrode was applied over the polyaniline (PANI) derivatives by thermal evaporation in a vacuum unit. The electrode had the form of an S-shaped track 1 mm wide.

In connection with the above and in continuation of our research on obtaining and studying the properties of hybrid molecules based on fullerenes and photochromic compounds, aimed at creating more efficient and promising organic electronic devices [51—56], we have manufactured and studied a photocontrolled OFET containing pyrrolidinofullerene 1 as the active layer (Fig. 7a). At the same time, for a strict and objective comparison of the results we obtained with literature data, we have manufactured a multilayer transistor in which the semiconductor (fullerene C60) and the light-controlled compound (spiropyran SpOx) formed separate layers (Fig. 7b) [57].

Table 1. Conditions for the synthesis of polymers by mixing with acid in various proportions with an oxidizing agent, indicating the reaction yield [50].

Polymer	Acid (0.2 M)	Oxidizer (7.75 mmol)	Yield, %
1	HCl	$FeCl_3$	21
2	H_2SO_4	$(NH_4)_2S_2O_8$	62
3	H_2SO_4	$FeCl_3$	29
4	HNO_3	$(NH_4)_2S_2O_8$	74
5	HNO_3	$FeCl_3$	42
6	$HClO_4$	$(NH_4)_2S_2O_8$	53
7	$HClO_4$	$FeCl_3$	55
8	HCl	$(NH_4)_2S_2O_8$	72
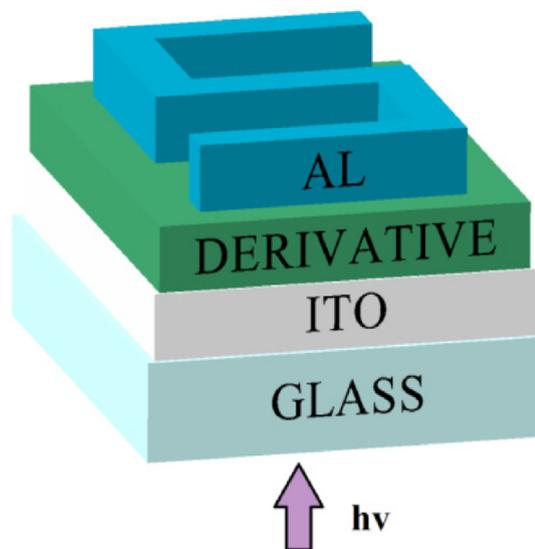
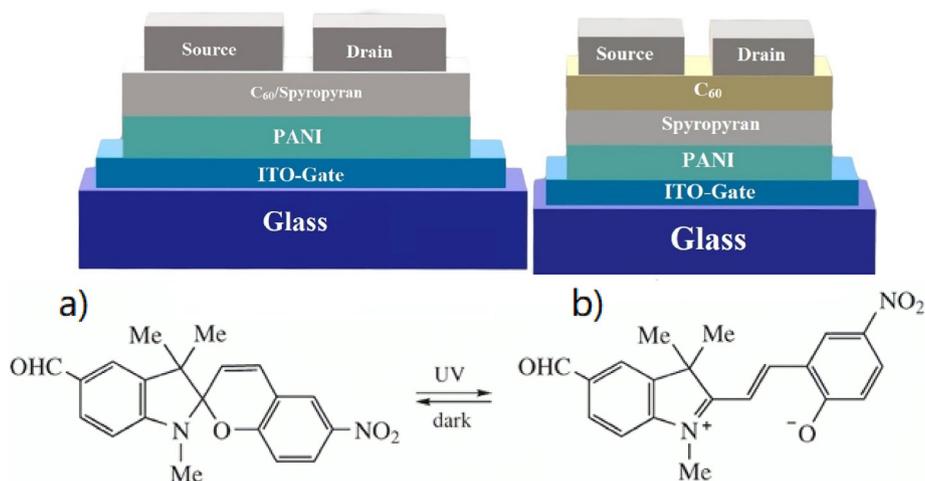Fig. 6. Structure of a photoresistor with a film of polyaniline derivative [50].

Fig. 5. Structures of optically controlled (a) mixed-type and (b) multilayer OFETs and the reversible UV light-induced isomerization of spiropyran 1 into its merocyanine form [49].
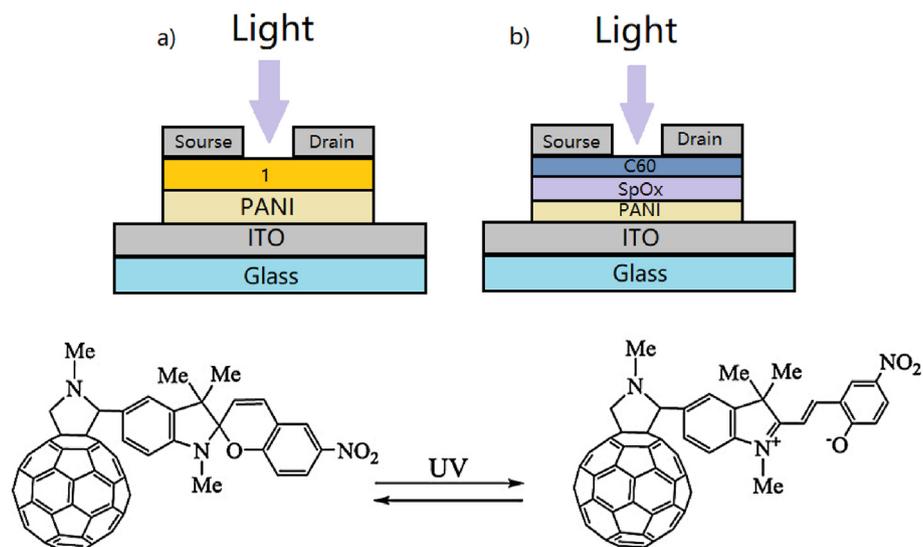
Fig. 7. Structures of photocontrolled OFETs. The following shows the reversible isomerization of the spiropyran moiety to the merocyanine form in hybrid molecule 1 in OFET (a) and the model spiropyran SpOx to the merocyanine in OFET (b) induced by UV irradiation [57].
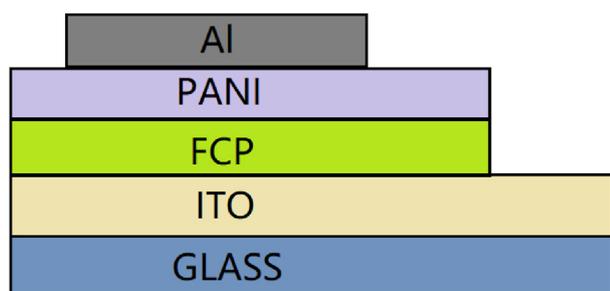

Fig. 8. Multilayer structure of FES film [58].

Fig. 9. Relaxation kinetics of I_{DS} OPT based on PVK:Ni (Ni concentration ~ 10 wt%) when turning on and off light with power ~ 60 $\mu W/cm^2$) $V_{DS} = -10$ V and $V_G = -8$ V [27].

Solar cells, especially organic solar energy photo-converters (photovoltaic solar cells (PVSC) are used for the conversion of the solar energy into electricity. Fig. 8 shows the structure of a photoconverter in which thin films of PANI derivatives and a fullerene-containing polymer (FCP) based on monosubstituted derivatives of 1,2-dihydro-C60 are used as photoactive layers [58].

3. Photoresponce kinetics

A typical character of the I_{DS} current relaxation kinetics for a PVK:Ni (Ni ~ 10 wt%) OCT when turning on and off light (with a power of ~ 60—70 $\mu W/cm^2$) at $V_{DS} = -10$ V and $V_G = -8$ V is shown in Fig. 9, where I_{DS} drain-source current, V_G is the gate voltage, V_{DS} is the drain-source voltage, and V_{th} is the threshold voltage.

The photoresponse kinetics of thin-film structures based on polyindole has been studied in Ref. [48]. To determine it, the change in photoconductivity was measured when a sequence of rectangular light pulses with a duration of 5, 10 and 5 s was applied. The
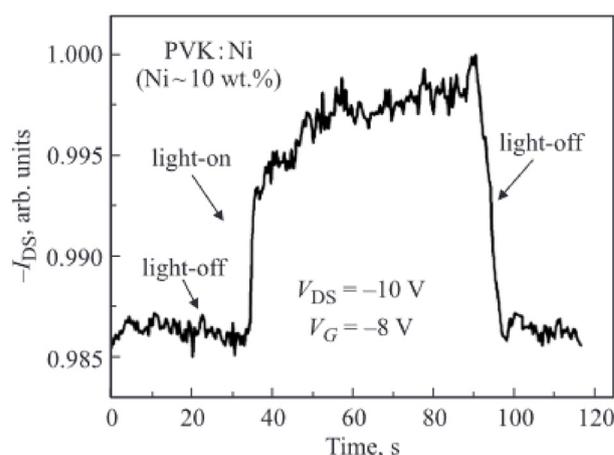
results are shown in Fig. 10. It turned out that the photoresponse of the transistor tracks the shape of the light pulses well, and the rise and fall time of the photocurrent pulse does not exceed 1 s. A shorter time is typical for structures obtained at high rotation speeds during centrifugation.

Fig. 11 shows typical I_{DS} current relaxation kinetics for an OFET when turning on and off the light (2—3 W/cm^2) at $V_{DS} = 3$ V and $V_G = 3$ V. The output current depends on the irradiation time of the conducting channel, and the maximum value is reached 12 s after turning on the light. The initial state of the transistors is restored 1—2 s after turning off the activating radiation. It is evident from Fig. 11 that the current in the mixed-layer transistor begins to increase after 3 s,
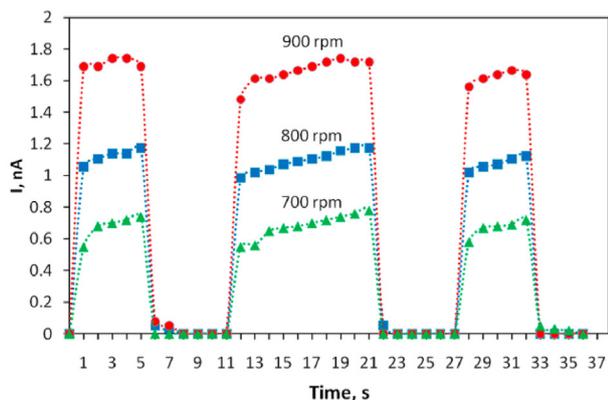
Fig. 10. Photoresponce kinetics of current through polyindole films obtained at different spin-coating rates. Voltage between electrodes U = 10 V [48].
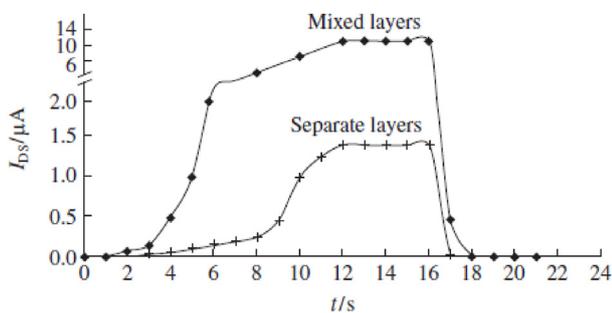

Fig. 11. Kinetics of I_{DS} increase and decrease for OFETs based on separate and mixed active layers upon UV light on and off (2–3 μW/cm^2, 350 nm) V_{DS} = 3 V and V_G = 3 V [49].
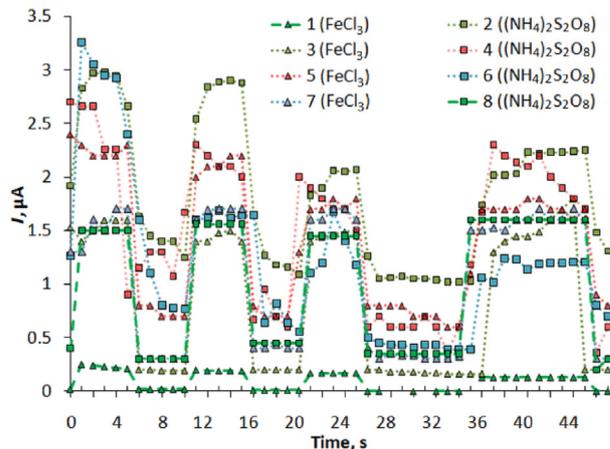

Fig. 12. Dependence of current on irradiation time at a voltage of 10 V and a distance of 10 mm from the radiation output of the fiber optic cable to the sample [50].
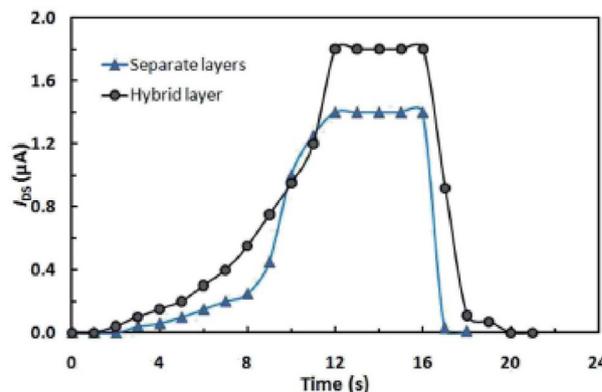

Fig. 13. Kinetics of IDS current rise and fall for OFETs based on double layers and hybrid layer 1 when UV light is turned on and off (150 W, 350 nm), V_{DS} = 3 V, V_G = 3 V [51].

whereas the multilayer device begins to operate 6–8 s after turning on the light. This is apparently due to a smaller number of photons reaching the photochromic layer in the latter transistor due to absorption in the organic semiconductor film [49].

For this purpose, the change in photoconductivity was measured when applying a sequence of rectangular light pulses with a duration of 5 s or 10 s. It is evident that the rise and fall time of the photocurrent pulse does not exceed 1 s. As can be seen from Fig. 12, the values of the current through the photoresistors during the action of the illumination pulse exceed 1 μA, only for one substance under number 1 the photocurrent was less than 0.4 μA. Samples under numbers 2, 5, 7, 8 have a higher current, after irradiation with four pulses, which indicates good stability of the samples. For the remaining samples, the current remains approximately at the same level, and sample under number 1 has the lowest current [50]. The decoding of the samples, their synthesis and chemical formulas are given in Table 1.

Fig. 13 shows that the current in the hybrid compound-based OFET is higher than in the multilayer device, which is explained by the fact that in the latter case fewer photons reach the photochromic layer as a result of absorption in the organic semiconductor. It is seen that the output current depends on the irradiation time of the conductive channel, and the maximum values are reached within 12 s after turning on the light [51].

4. Photosensitivity, charge transfer and output characteristics

The charge carrier mobility in the OFET active layer m was estimated from equation (1) for the low field mode:

$$\mu = I_{DS} L / (WC(V_G - V_{th})V_{DS}), \qquad (1)$$

where W is the channel width, L is the channel length, C is the capacity per area of gate dielectric PANI (for 500

nm thickness, C = 0.7 nF/cm^2), V$_G$ is the gate voltage, V$_{DS}$ is the drain-source voltage, and V$_{th}$ is the threshold voltage.

The response of fabricated transistors to external influence was evaluated using the photosensitivity (P) and responsivity (R) characteristics. The P value is defined as the photocurrent to dark current ratio:

$$P = I_{ph} / I_{dark} = (I_{illum} - I_{dark})/I_{dark}, \qquad (2)$$

where I$_{ph}$ is the photocurrent, I$_{illum}$ is the channel current under illumination, and I$_{dark}$ is the drain current in the dark.

The R value was defined as the ratio between the generated photocurrent and the incident optical power (P_{opt}); hence, the responsivity R can be calculated as

$$R = I_{ph}P_{opt} = (I_{illum} - I_{dark})/aE_{opt}, \qquad (3)$$

where E_{opt} is the incident radiation power density and a is the area accessible for incident radiation.

When PVK:Ni-based OPTs are illuminated with a sunlight simulator with a power of ~ 60—70 μW/cm^2 at V$_G$ = −10 V and V$_{DS}$ = −10 V, their efficiency reaches ~ 1.2 and ~ 5.3 A/W for samples with a Ni content of ~ 5 and ~ 10 wt%, respectively, while the efficiency values of PVK:Ni-based photosensitive OPTs increase with increasing gate bias V$_G$ [27].

The estimated value of the carrier mobility is m (MPIn) = 0.016 cm^2 V^{-1} s^{-1} [48], which is comparable to mobility for this class of compounds [59].

The photosensitivity estimation from equation (3) gave values of 14,000 and 1400 for the phototransistor based on the film made of binary mixture and for

separately deposited films, respectively. The calculated responsivity values were ranged from 1.4 to 3 mA/W for the transistor made of binary mixture and 10 times less for that containing the separate layers. During the calculations, it was taken into account that the device area exposed to the light did not exceed 5·10^{-3} cm^2. Thus proceeding from the emitter characteristics, which provided an incident power density of approximately 2—3 W/cm^2, the overall radiation density on the phototransistor was about 10 μW [49].

Photosensitivity (P) and responsivity (R) for samples 1—8 (the numbering of the samples is given in Table 1) were calculated using formulas (2) and (3) and are presented in Table 2.

The photosensitivities estimated by relation (3) were 1800 and 1400 for the phototransistor based on fullerene C60 and spiropyran hybrid and the phototransistor fabricated with separate deposition, respectively. The responsivity calculation yielded the values of 180 μA/W for the hybrid transistor and 140 μA/W for the separate-layer transistor. The calculations assumed that the area of the device accessible to the incident light was not more than 5·10^{-3} cm^2. Then, considering the emitter characteristics which provide the incident power density of approximately 2 W/cm^2, we obtain the overall radiation power on the phototransistor to be about 10 μW [51].

The families of output and transfer current-voltage characteristics of the phototransistor are shown in Fig. 14. The study of the current-voltage characteristics of the manufactured transistors showed that in the absence of irradiation, the currents in the phototransistors are about 1 nA or less. Irradiation of the transistor gap areas with ultraviolet light (350 nm) increases the drain-source current by three orders of magnitude [48].

Fig. 15 shows the transfer and output characteristics of the OPT. In all cases, the currents for structures with a hybrid layer of molecule 1 (Fig. 7) exceeded the current values for structures with separate layers by

Table 2. Calculated values of photosensitivity and sensitivity [50].

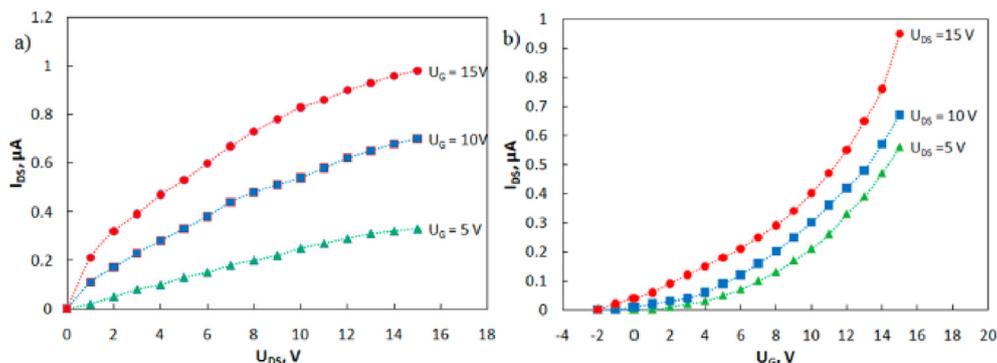| Samples	1	2	3	4	5	6	7	8
P	400	2800	2000	2500	3000	2300	2900	1500
R, μA/W	1108	7777	5552	6941	8330	6386	8052	4163

Fig. 14. Family of (a) output and (b) transfer current-voltage characteristics of the phototransistor [48].
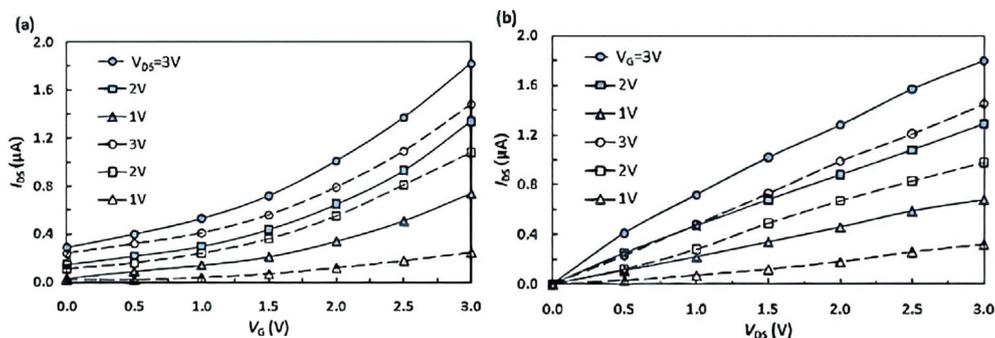
Fig. 15. (a) Transfer and (b) output characteristics of OFETs based on hybrid (solid lines) and separate (dashed lines) active layers [51].

several tenths of microamperes (μA). An increase in currents in the created OPTs is observed with a positive voltage on the gate, which corresponds to the electron type of conductivity of the OPT transport channel [51].

The study examined new nanocomposite thin-film materials for the creation of chemical gas sensors, phototransistors and photoresistors. The results showed the potential of using these materials due to their unique properties, such as high sensitivity, response speed and selectivity. This opens up opportunities for the development of more efficient and accurate sensors, as well as for the improvement of electronic devices based on photonic effects [60−70].

5. Conclusion

Organic phototransistors and photoresistors are key components in the field of photonics and optoelectronics, providing high sensitivity and controllability in response to light signals. Their operating principle is based on the conversion of light energy into electrical signals, which makes them indispensable in various applications, including sensors, solar cells and displays. One of the important aspects is photosensitivity, which determines the ability of the device to register even weak light fluxes. Organic phototransistors, as a rule, demonstrate a higher level of photosensitivity compared to classic inorganic analogs due to the improved structure of materials and deposition technology. Analysis of the output and input characteristics of transistors shows that organic devices are capable of providing flexibility in settings and design.

That introduction of photosensitive spirooxazine film at the interface between the semiconductor and dielectric layers in OFET represents a highly promising approach for construction of multibit optical memory elements with advanced electrical characteristics, good stability and reliability.

The manufactured thin-film phototransistors based on polyindole thin films have good characteristics such as quantum efficiency and carrier mobility. The studied form of polyindole has high solubility, so the production of electronic components is compatible with modern technology of printed organic electronics.

The studied photoresistive structures 1−8 may prove to be very promising when used in security alarm systems and in optical memory cells. The sensitivity of the photoresistive structures was measured and reached values of 8330 $\mu A \cdot W^{-1}$, the photosensitivity reached values of 3000. All measurements were carried out under normal conditions, i.e. in atmospheric air, which is an advantage of the studied photoresistive structures compared to most experimental structures based on other compounds that require operation in a chamber with inert gas or dry nitrogen.

In addition, organic phototransistors and photoresistors will be lightweight and thin, making them ideal for integration into wearable devices and flexible displays. These properties will enable the creation of more convenient and multifunctional products that can adapt to the needs of users and the environment. In turn, this will lead to increased interest from manufacturers in creating innovative solutions based on them. An equally important aspect will be the reduction in the cost of producing organic components compared to inorganic analogs. The use of simple deposition technologies such as printing and spinning will ensure mass production at low costs, making organic phototransistors and photoresistors available for a wide range of applications. Given the constant progress in the field of materials science, new organic compounds and compositions are expected to offer even higher characteristics and improved performance. This will allow not only to improve existing technologies, but also to create completely new devices that will provide new levels of interaction with the world around us, transforming areas from healthcare to consumer electronics.

Conflict of interest

The authors state that they are clear of any financial conflicts of interest.

Funding and Acknowledgments

References

[1] R.L. Petritz, Phys. Rev. 104 (6) (1956) 1508.
[2] R.S. Crandall, Semiconduct. Semimet. 21 (1984) 245−297.
[3] T.S. Moss, Rep. Prog. Phys. 28 (1) (1965) 15.
[4] N.V. Joshi, Photoconductivity, New York: Routledge, 2017, p. 304.
[5] M. Freitag, et al., Nano Lett. 3 (8) (2003) 1067−1071.
[6] M. Brinza, et al., J. Mater. Sci. Mater. Electron. 16 (2005) 703−713.
[7] S.O. Kasap, et al., Tech. Appl. 1 (2022) 1−88.
[8] L.E. Barros, et al., IEEE Trans. Microw. Theor. Tech. 45 (8) (1997) 1368−1374.
[9] Y. Betser, et al., J. Lightwave Technol. 16 (4) (1998) 605.
[10] S. Blayac, et al., in: International Conference on Indium Phosphide and Related Materials, 2000, pp. 481−484.
[11] J.C. Campbell, J. Appl. Phys. 53 (2) (1982) 1203−1208.
[12] J.C. Campbell, in: Semiconductors and Semimetals vol. 22, Elsevier, 1985, pp. 389−447.
[13] M. Brinza, et al., J. Mater. Sci. Mater. Electron. 16 (2005) 703−713.
[14] V.M. de-Los-Rios, et al., Micromachines 15 (5) (2024) 579.
[15] S.R. Saitov, et al., Org. Electron. 112 (2023) 106693.
[16] C.A. Leatherdale, et al., Phys. Rev. B 62 (4) (2000) 2669.
[17] H.B. De Vore, Phys. Rev. 102 (1) (1956) 86.
[18] D.A. Anderson, et al., Phil. Mag. 36 (3) (1977) 695−712.
[19] R. Frerichs, Phys. Rev. 72 (7) (1947) 594.
[20] S.A. Studenikin, et al., J. Appl. Phys. 91 (8) (2002) 5060−5065.
[21] R.L. Petritz, Phys. Rev. 104 (6) (1956) 1508.
[22] A. Rammohan, et al., in: IOP Conference Series: Materials Science and Engineering, 2017 062056, 263(6).
[23] P.Å. Öberg, Sensor. Update 13 (1) (2003) 201−232.
[24] N. Kumar, et al., in: 2011 7th International Wireless Communications and Mobile Computing Conference, 2011, pp. 1513−1518.
[25] K. Shaaban, J. Traffic Transport. Eng. 8 (4) (2021) 483−492.
[26] L.A. Frolova, et al., Chem. Commun. 51 (28) (2015) 6130−6132.
[27] A.N. Aleshin, et al., Phys. Solid State 54 (8) (2012) 1586−1590.
[28] C. Xie, et al., Adv. Funct. Mater. 30 (20) (2020) 1903907.
[29] J. Fu, et al., Nano Lett. 23 (11) (2023) 4923−4930.
[30] A. Tavasli, et al., Electronics 11 (3) (2022) 316.
[31] Y.C. Lin, et al., Small Sci. 2 (4) (2022) 2100109.
[32] C. Wang, et al., Chem. Soc. Rev. 49 (3) (2020) 653−670.
[33] A.K. Ghosh, et al., Adv. Funct. Mater. 33 (23) (2023) 2210172.
[34] J. Liu, et al., J. Mater. Sci. Mater. Electron. 32 (2021) 11326−11333.
[35] M.K. Bakhadirkhanov, et al., Tech. Phys. Lett. 47 (9) (2021) 641−644.
[36] https://www.circuitstoday.com/photoresistor.
[37] L. Wang, In International Conference on Advances in Mechanical Engineering and Industrial Informatics. Atlantis Press, (2025).
[38] A. Singh, et al., in: Optical Properties and Applications of Semiconductors, 2022, pp. 75−90.
[39] M. Daanoune, et al., J. Appl. Phys. 127 (5) (2020).
[40] R.B. Salikhov, et al., Emerg. Solar Energy Mater. (2018) 83−104.
[41] M. Wright, et al., Sol. Energy Mater. Sol. Cell. 107 (2012) 87−111.
[42] A.M. Bagher, Int. J. Sustain. Green Energy 10 (3) (2014) 53−58.
[43] H. Hoppe, et al., J. Mater. Res. 19 (7) (2004) 1924−1945.
[44] T.M. Clarke, Chem. Rev. 110 (11) (2010) 6736−6767.
[45] P. Cheng, et al., Chem. Soc. Rev. 45 (9) (2016) 2544−2582.
[46] J. Liang, et al., J. Am. Chem. Soc. 138 (49) (2016) 15829−15832.
[47] Q. Ta, et al., Energy Environ. Sci. 12 (8) (2019) 2375−2405.
[48] R.B. Salikhov, et al., Materials 15 (1) (2021) 228.
[49] A.R. Tuktarov, et al., Mendeleev Commun. 29 (2) (2019) 160−162.
[50] R.B. Salikhov, et al., Lett. Mater. 14 (2) (2024) 113−118.
[51] A.R. Tuktarov, et al., RSC Adv. 6 (2016) 71151.
[52] V.A. Pomogaev, et al., Phys. Chem. 122 (2018) 505.
[53] A.R. Tuktarov, et al., Mendeleev Commun. 25 (2015) 470.
[54] A.R. Tuktarov, et al., Tetrahedron Lett. 56 (2015) 7154.
[55] A.R. Tuktarov, et al., Mendeleev Commun. 26 (2016) 143.
[56] A.R. Tuktarov, et al., Org. Chem. 53 (2017) 891.
[57] R.B. Salikhov, et al., RSC Adv. 9 (13) (2019) 7505−7508.
[58] R.B. Salikhov, et al., Tech. Phys. Lett. 39 (2013) 854−857.
[59] P.-L.T. Boudreault, et al., Org, Electron 11 (2010) 1649.
[60] A.G. Mustafin, et al., RSC Adv. 11 (34) (2021) 21006−21016.
[61] A.G. Mustafin, et al., Macromolecules 53 (18) (2020) 8050−8059.
[62] R.B. Salikhov, et al., Lett. Mater. 12 (4) (2022) 309−315.
[63] A. Bunakov, et al., Macromol. Symp. 212 (1) (2004) 387−392.
[64] R.B. Salikhov, et al., Lett. Mater. 13 (2) (2023) 132−137.
[65] R.B. Salikhov, et al., Phys. Solid State 49 (2007) 185−188.
[66] A.G. Mustafin, et al., Macromolecules 53 (18) (2020) 8050−8059.
[67] L.R. Latypova, et al., Polym. Int. 69 (9) (2020) 804−812.
[68] A.R. Tameev, et al., Phys. Solid State 53 (2011) 195−200.
[69] A.N. Andriianova, et al., New J. Chem. 45 (14) (2021) 6356−6366.
[70] R.M. Gadiev, et al., JETP Lett. 90 (2010) 726−730.