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Photosensitive structures on the basis of magnetic semiconductors FeIn$_2$S$_4$

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Abstract. In this work, which is in line with the new promising areas of semiconductor electronics, we present the results of a study of the photovoltaic properties of photosensitive structures based on Fe and In$_2$S$_4$ to define the application prospects of this new magnetic semiconductor for use in photonics.

1. Introduction

The study of magnetic semiconductors A$^{II}$B$_2$$^{III}$C$_4$$^{IV}$ (A$^{II}$-Mn, Fe, Co, Ni, B$^{III}$-Al, Ga, In, C$^{IV}$-S, Se, Te) has received increased attention in recent years [1]. We can say that these materials are new and unexplored. These materials are promising for photonics. This work is dedicated to the creation and study of photosensitive structures on the basis of FeIn$_2$S$_4$ single crystals one of the most promising materials for magnetic optical nanodevices for recording, storing and transmitting information. The problems with growing single crystals of these substances, development of electronic structures based of them, and comprehensive studies of their physical properties remain unresolved so far for the majority of the new multicomponent substances. Such ternary compound FeIn$_2$S$_4$ is one of these

![Figure 1](image-url)

Figure 1. The block diagram of the optical system with photodetector: (1) emitter; (2) modulator; (3) polarizer; (4) photodetector; (5) amplifier.
substances, which, in addition, possesses magnetism. In the literature, there is only information on some crystallochemical characteristics of these compounds [2, 3]. In this work, which lies in the tideway of a new promising trend of semiconductor electronics, we show the results of first studies on the growth of FeIn$_2$S$_4$ single crystals and creation of the first photosensitive structures on their basis. Such photosensitive structures made it possible to begin the first studies of their photoelectric properties and to determine the applied prospects of this new magnetic semiconductor. Optical system is an optoelectronic product, which includes photodetector that is designed to convert the input optical signals to electronic equipment in electrical. A typical block diagram (Fig. 1) of such a system includes an optical radiation source, a modulator, a polarizer, a fiber optical line, photodetector, an amplifier. As such, the device may convert optical signals from the optical linear path, electric signal conversion device, for example, the electronic equipment of the receiving station. The detector uses different photosensitive structures on the basis of isotropic and anisotropic semiconductors. These photo detectors can become more interesting for use as photodetectors in the emerging areas spintronics and Photonics, due to the presence in the composition of Fe.

2. The method

The single crystals of FeIn$_2$S$_4$ were grown by the directional crystallization method of an almost stoichiometric melt of this compound. The synthesis of such crystals was carried out by the two temperature method from the parent elements of purity no less than 99.999 wt %. The ingot synthesized was ground and placed into a double quartz ampoule; the internal ampoule had a cylindrical capillary at its end, which ensured the formation of the single crystal seeding. After the evacuation of the ampoule to a residual pressure of $\sim 10^{-3}$ Pa, it was placed into a vertical one zone furnace. The temperature in the furnace was increased at a rate of $\sim 100$ K/h to 1400 K and, for the homogenization of the melt, was maintained at this temperature for 2 h, after which the directional crystallization of the melt was conducted by reducing the temperature at a rate of $\sim 2$ K/s until complete solidification of the melt. For the homogenization of the ingots obtained, they were annealed at $\sim 1020$ K for 150 h. This regime made it possible to reproducibly grow single crystal ingots with a diameter of $\sim 14$ mm and a length of $\sim 40$ mm. The elemental composition of the single crystals was determined by electron microprobe analysis on a Cameca SX 100 device; an error of determining the element concentrations did not exceed $\pm 5$ wt %. The structure of the crystals obtained was determined by X-ray diffraction. The X-ray diffraction patterns were recorded on an automated computer aided DRON-3M diffractometer in Cu CuKa radiation with a graphite monochromator.

The results of the analysis of composition of the FeIn$_2$S$_4$ ingots showed that the content of elements in the single crystals (Fe : In : S = 13.94 : 28.34 : 57.72 at %).

The schematic diagram for the study of the photosensitivity based on the method of measurement of the photocurrent short-circuit depending on the length of the incident light beam. Light is incident on the receiving plane of the structure along the normal to the receiving plane. For the production of such studies, we used a source of monochromatic radiation with the degree of linear polarization of approximately 100 %. To do this, use lamp RV-24 and a monochromator (SPM-2). The circuit includes a modulator for monochromatic radiation (frequency 40 Hz) and the adjustment device (STF-1) with a semiconductor pattern and ohmic contacts, as well as the scheme of synchronous detection system with computer control of the experiment and display the results on screen.

3. Results and discussion

As was established in the course of the first studies of contact phenomena, the photosensitive structures can be reproducibly created using thermal vacuum deposition of thin layers of indium and aluminum onto mechanically and chemically polished substrates, as well as on the cleavage surfaces of FeIn$_2$S$_4$. An ohmic contact was produced by the chemical deposition of copper from an aqueous solution of Cu$_2$SO$_4$ or by applying a silver paste. According to the carried out measurements of the stationary current–voltage characteristics of the In(Al)/FeIn$_2$S$_4$ structure, they indicate a rectification
with a coefficient \( K \approx 5 \) at the bias voltages \( U \approx 0.5 \) V at 300 K. The forward direction corresponds to the positive polarity of the external bias on the FeIn\(_2\)S\(_4\) crystal. Upon illumination of surface barrier

![Image](image_url)

**Figure 2.** Relation quantum efficiency spectra of In/FeIn\(_2\)S\(_4\), when illumination from the side of semiconductor (1), and when illumination from the side of surface (2).

structures, there reproducibly appears a photovoltaic effect. This photovoltaic effect have sign agrees with the direction of rectification and does not depend on the localization of the light probe (of the diameter of \( \sim 3 \) mm) on the surface of the structure, as well as on the intensity of illumination and photon energy. These specific features serve as a ground to connect them with the energy barrier created on the contact of the metal with the semiconductor. The voltage photosensitivity always predominates upon the illumination of the structures from the side of the barrier film, and in the best structures it reaches \( \sim 50 \) V/W at \( T = 300 \) K. Figure 2 displays the first spectra of the relative quantum efficiency of the photoconversion \( \eta(\omega) \) of the In/FeIn\(_2\)S\(_4\) structures calculated as the ratio of the short circuit photocurrent to the number of incident photons depending on the geometry of photodetection.

Upon the illumination of the structures from the side of the semiconductor, the \( \eta(\omega) \) spectra have a clearly pronounced shortwavelength edge (Fig. 2, curve 2), whereas upon illumination from the side of the barrier there occurs an increase in \( \eta \) instead of a drop. As a result, the \( \delta \) of the \( \eta(\omega) \) spectra grows from 0.2 to 1.2 eV, and the maximum of the photosensitivity \( \omega^\text{m} \) is displaced into the shortwave length region from 1.6 to 2.2 eV. The short wavelength drop in \( \eta \) at \( \omega > 1.6 \) eV (Fig. 2, curve 2) is displaced with decreasing thickness of the FeIn\(_2\)S\(_4\) plate into the short wavelength region because of a reduction in the radiation absorption in the substrate of this structure and, therefore, this can show its connection with the beginning of the fundamental absorption in FeIn\(_2\)S\(_4\). The high value of \( \delta \) (1.2 eV) upon the illumination of the In(Al)/FeIn\(_2\)S\(_4\) barriers from the side of the barrier layers demonstrates the high efficiency of the barriers obtained, which makes it possible to strongly suppress the effect of surface recombination upon the photoconversion in geometry 1 (Fig. 2). Consequently, as can be seen from Fig. 2, upon the illumination of the In(Al)/FeIn\(_2\)S\(_4\) structures from the barrier side the photosensitivity spectra are wideband and ensure photodetection in the range from 1.3 to 3.2 eV at 300 K. An analysis of the spectra of photoactive absorption of the In(Al)/FeIn\(_2\)S\(_4\) structures from the positions of the theory of fundamental absorption \([4,5]\) in the coordinates \( (\eta\omega)^{1/2} \) versus \( \omega \), and \( (\eta\omega)^2 \) versus \( \omega \) (Fig. 3) suggests that the edge of the interband absorption in FeIn\(_2\)S\(_4\) is formed by direct (Fig. 3, curve 1) and indirect (Fig. 3, curve 2) transitions, respectively, and the corresponding values of the energy gaps for direct (\( \delta \)) and indirect (\( \delta \)) interband transitions in FeIn\(_2\)S\(_4\) could be estimated from the extrapolation of
the appropriate dependences \((\eta \omega)^2\) and \((\eta \omega)^{1/2}\) to zero; then, from the cutoffs on the energy axis we obtain \(= 1.68\) eV and \(= 1.38\) eV for the undoped single crystals of FeIn\(_2\)S\(_4\) at 300 K.

Figure 3. Dependences \((\eta \omega)^2 = f(\hbar \omega)\) (curve 1) and \((\eta \omega)^{1/2} = f(\hbar \omega)\) (curve 2) for the In/FeIn\(_2\)S\(_4\) structure at \(T = 300\) K.

4. Conclusion

Thus, using the method of directional crystallization of the melt, we have possibility to grow single crystals of FeIn\(_2\)S\(_4\) with a conductivity of the p type and obtained for the first time photosensitive In(Al)/FeIn\(_2\)S\(_4\) Schottky barriers. We established that upon the illumination of the new structures from the barrier side, a wideband photovoltaic effect is reproducibly observed. It has been shown that, depending on the geometry of photodetection, a wideband or selective photosensitivity can be obtained. If we illuminate this structure from the side of barrier the photosensitivity spectra are wideband and demonstrates photodetection in the range 1.3-3.2 eV at room temperatures. Based on the results of the studies performed, it has been established that the edge absorption in FeIn\(_2\)S\(_4\) is formed by direct and indirect interband transitions; the width of the energy gap for these transitions has been estimated. A conclusion is made on the possibility of application of the new magnetic semiconductor FeIn\(_2\)S\(_4\) as wide band photodetectors for photonics and spintronics.

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