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Narrowband MSM Detector of the Visible Part of the Spectrum Based on a ZnCdSe/ZnSSe/GaAs Heterostructure

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Abstract—The results of experimental studies of photodiodes based on interdigital MSM (metal–semiconductor–metal) Schottky barrier contacts to a ZnCdSe/ZnSSe/GaAs heterobarrier structure are presented. The detector provides a narrowband response (FWHM = 4.3 nm) at a wavelength of 460 nm, a sharp drop in the photosensitivity in the short-wavelength part of the response signal, high ampere-watt sensitivity, and low dark current.

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INTRODUCTION

Open systems for the transmission of optical information signals, as a rule, are subject to the harmful effects of external factors: active and passive interference, background radiation from the Sun, etc. This leads to a decrease in the reliability of the information system and a decrease in its dynamic range. Filtration of the received optical radiation allows reducing the influence of external interference and to isolate the useful information signal. In this regard, an important problem is the development of narrow-band photodetectors [1–6]. Photodetectors of the visible part of the spectrum are promising for use in many industrial, scientific, and military applications (space, medicine, environmental research, etc.) [6]. Until recently, the detection of visible and UV radiation was performed exclusively with Si and GaAs detectors. One of the drawbacks of detectors based on these materials is the degradation of their parameters ("aging") when exposed to radiation with an energy significantly exceeding the band gap of Si and GaAs [3, 7]. Another disadvantage of Si and GaAs receivers is that their maximum photosensitivity is in the longer-wavelength infrared region of the spectrum, and the implementation of noise-immune narrow-band reception requires the use of external filters [3, 6, 7]. Recently, filters of transmitted visible radiation based on interference interaction in ultrathin semiconductor Si-structures placed between two metal films [8] have been proposed; in another method, visible radiation was filtered using chemical pigments [9]; finally, filters based on surface plasmon polaritons have recently appeared [8]. It should be noted that all these filters, like many others, are external with respect to the photodetector and their use leads to a complication of the receiving system and a decrease in sensitivity [3, 6, 7].

A wide-gap semiconductor itself is an important advantage from the point of view of creating photodetectors based on it, since it allows one to realize low dark currents and high reliability under illumination with high-energy photons, and by choosing heteroepitaxial layers, a narrow-band response of the detector can be realized, which will provide filtering of useful information signal and thus noise immunity of the optical information system. It is also known that wide-gap semiconductor materials have significantly higher thermal conductivity and radiation resistance compared to Si and GaAs. For comparison, the thermal conductivity of GaAs and ZnSe at room temperature are, respectively, 1.49 and 18 W m^{-1} K^{-1}. This makes it possible to use devices based on them at significantly higher temperatures and powers of received radiation, while the strength of the chemical bonds of wide-gap materials leads to their increased radiation resistance [3].

Thus, the development and creation of narrow-band detectors based on heterostructures of wide-gap semiconductor materials is an urgent problem of modern optoelectronics.

Various types of detectors based on widegap semiconductor materials and heterostructures were studied in [10–14]. Paper [10] presents the results of investigations of metal–semiconductor–metal (MSM) detectors based on a ZnSTeSe epitaxial layer grown on a GaAs substrate. Although a rather sharp drop in the response of the detector at a wavelength of 500 nm was obtained, the detector demonstrated a broadband response in the wavelength range of 350–500 nm and did not meet the requirements for selective narrowband reception of an optical signal. In [11], a photodetector based on a ZnSTeSe/ZnSe heterostructure grown on a GaAs substrate was studied. A sufficiently effective broadband detector response in the spectral range of 305–900 nm with maximum photosensitivity at a wavelength of ~800 nm is realized here, due to the presence of a GaAs substrate. We recently investigated the detecting properties of MSM diodes based on low-dimensional heterostructures with ZnCdS quantum wells separated by ZnMgS barrier layers, which provided two-color narrow-band detection of radiation at wavelengths of 350 and 450 nm [12]. However, the bandwidth of the spectral response of the detector was quite large: at a wavelength of 450 nm, the FWHM of the detector response signal was 50 nm. In [13], MSM detectors based on GaN/AlGaN quantum wells were created and studied. When illuminated from the side of the substrate, the response of the detector was obtained in the wavelength range of 297–352 nm, i.e., FWHM ~ 60 nm. A narrowband spectral response with FWHM = 27 nm was realized in our studies at a wavelength of 240 nm on an AlGaN/AlN MSM photodiode [14]. However, in the last two examples, the heterostructures were grown on sapphire substrates, which creates great difficulties in integrating such detectors with amplification and signal processing circuits. Finally, quite recently, the authors of [6] published the results of studies of narrow-band photodetectors based on polymer perovskite layers. A narrowband response of the detector with FWHM = 50 nm was obtained with the possibility of adjusting the maximum sensitivity in the range of 680–710 nm. As you can see, narrow-band detectors of the visible and UV part of the spectrum have been the subject of intensive research in recent years.

In this study, we investigated the possibility of reducing the width of the spectral response of a photodetector in the visible part of the spectrum in order to achieve FWHM in the range of nanometers while maintaining a high quantum efficiency of the detector. The detector is implemented in the form of interdigital Schottky MSM barrier contacts to the ZnCdSe/ZnSSe/GaAs heteroepitaxial structure and provides a narrow-band response (FWHM = 4.3 nm) at a wavelength of 460 nm, high ampere-watt sensitivity, and low dark current.

RESULTS

A surface-barrier planar diode based on double rectifying contacts in the metal–semiconductor–metal system (MSM diode) was chosen as the basic photodiode structure [15–17]. The MSM diode is implemented in the form of interdigital Schottky barrier contacts to the ZnCdSe/ZnSSe heterobarrier structure grown by metalorganic vapor phase epitaxy (MOVPE) on a semi-insulating (SI) GaAs substrate 300 nm thick (Fig. 1). Epitaxy was preceded by 1-min annealing of the substrate at a temperature of 600°C in a hydrogen atmosphere in order to deoxidize its surface. The deposition of the heterostructure was carried out at a hydrogen pressure close to atmospheric in a slit quartz reactor with in-situ control of the reflection spectrum at a wavelength of 730 nm. The deposition temperature was 450°C. Diethylzinc, dimethylcadmium, diethylselenide, and diethylsuldide were used as starting materials. The ZnSSe (132 nm) and ZnCdSe (805 nm) layer thickness was calculated from the reflection spectra. By means of photolithography, interdigital contacts of an MSM diode with a width of 2 μm and a distance between them of 4 μm were formed on the surface of the heterostructure. Ni was used as the metal forming the Schottky barrier. The total detector area was 100 × 100 μm^2.

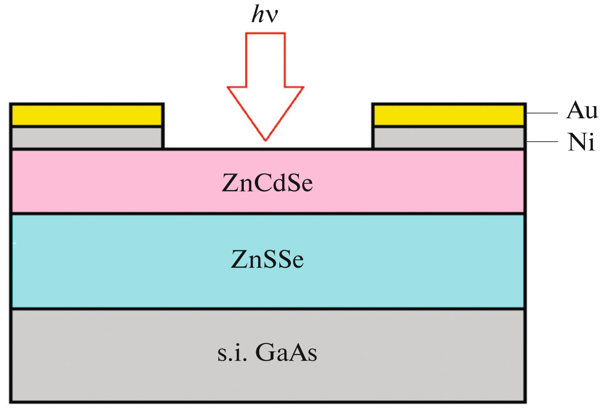

Fig. 1. Heterostructure and interdigital contacts of an MSM diode.

The current–voltage (*I*–*V*) characteristics of the fabricated MSM heterophotodiodes were investigated at room temperature on an Agilent B 1500 A semiconductor device meter. They are shown in Fig. 2 at different bias voltage directions and exhibit low dark currents at sufficiently high voltages. At a bias voltage of 30 V, the dark current is 2×10^{-10} A, which is comparable to the dark currents of MSM diodes based on the low-dimensional ZnCdS/ZnMgS/GaP heterostructure [12]. Since shot and backward frequency noise are proportional to the amount of current flowing through the junction, the low dark current allows the detector to increase the signal-to-noise ratio. The dark current is described in terms of the theory of thermionic emission. In this case, the height of the potential barrier in the investigated interdigitated system of contacts of the MSM, according to measurements performed by the method of [18], was 1.1 eV, and the coefficient of ideality of the Schottky barrier is 1.16. These parameters indicate the high quality of the Schottky barriers in the investigated MSM diodes. It should be noted that the positive and negative branches of the *I*–*V* characteristic of the investigated MSM diode are slightly asymmetric due to differences in the densities of states at

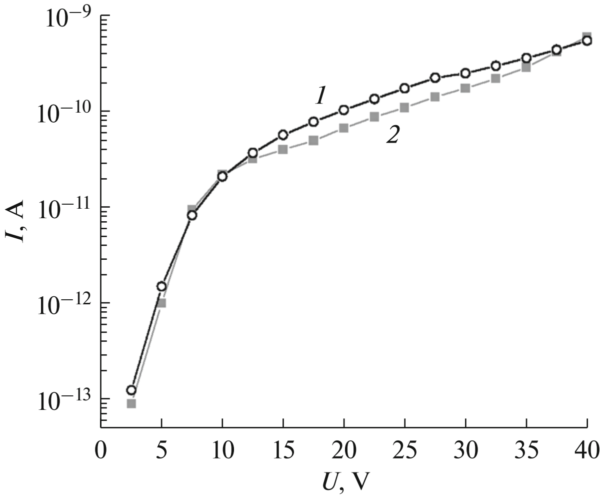

Fig. 2. Current–voltage characteristics of the MSM heterophotodiode: (*1*) forward bias; (*2*) reverse bias.

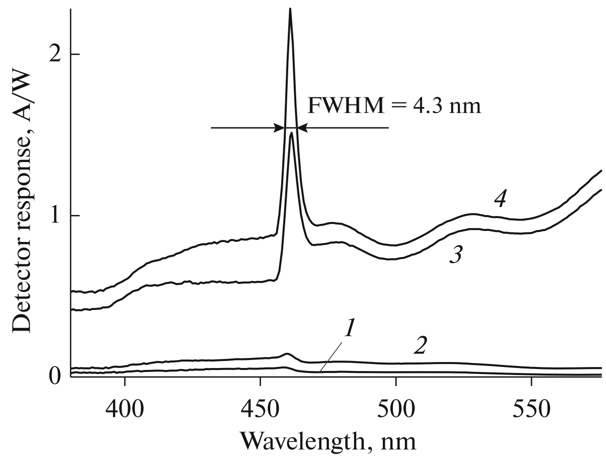

Fig. 3. Spectrum of the photoresponse signal of the MSM detector: bias 5 (*1*), 10 (*2*), 20 (*3*), and 30 V (*4*).

the metal–semiconductor interface of two contacts and growth defects, which lead to surface irregularities of the grown semiconductor structure and, as a consequence, to unequal effective contact areas. The breakdown voltage of the detector was ~90 V.

The spectral dependence of the photosensitivity of the investigated MSM diode was measured using a halogen lamp as a radiation source, a monochromator, a modulator, and a selective voltmeter using the mode of synchronous detection of the electrical response signal from the MSM heterophotodiode. The ampere–watt sensitivity was determined as the ratio of the detector photocurrent to the power of optical radiation incident on the MSM diode. The radiation power was measured with a calibrated silicon photodiode. Figure 3 shows the spectrum of the detector photoresponse signal at various bias voltages. The detector is quite narrowband, measured at a wavelength of 460 nm, the FWHM of the response signal is 4.3 nm, is the smallest known, is published in the literature for detectors of radiation in the visible part of the spectrum, and allows a high level of filtering of the useful information signal.

It was shown in [3, 19] that photodetectors based on ZnSSe provide a sharp drop in sensitivity in the long-wavelength part of the detector response signal ("red" boundary). This is observed in our experiments (see Fig. 3). It is known that the absorption depth of optical radiation in ZnSSe at a wavelength of 460 nm is ~500 nm [20]. When switching to the detection of optical signals at shorter wavelengths, with an increase in the energy of a light quantum, the absorption coefficient of the radiation incident on the detector sharply increases. In this case, it is absorbed closer to the surface of the ZnCdSe/ZnSSe heterostructure. In this case, the concentration of photogenerated electrons and holes is very high, which decreases the carrier lifetime and, accordingly, increases the probability of surface and bulk recombination [21]. The carriers recombine before they go to the interdigitated contacts of the diode. An excessive level of defects at the ZnCdSe/ZnSSe interface also leads to carrier capture processes and a sharp drop in the detector photoresponse signal. We explain the sharp drop in the photosensitivity in the short-wavelength part of the detector response signal both by the strong surface and bulk recombination of photoinduced charge carriers in the thin upper ZnCdSe layer and by the recombination at a high defect density at the interface of the lattice-mismatched ZnCdSe/ZnSSe layers.

Simulation within the framework of a two-dimensional model [16] shows that at bias voltages <10 V and a gap between interdigital contacts of 4 μm, the detector operates under conditions of partial depletion of the active intercontact region. This is confirmed by a significant decrease in the detector response signal in the range of bias voltages of 5–10 V. An increase in the bias voltage leads to a complete depletion of the intercontact region and significantly increases the efficiency of the narrow-band detector. At a bias voltage of 30 V, the photoresponse signal of the MSM diode at a wavelength of 460 nm, taking into account the reflection loss from the interdigital contacts, corresponds to an ampere–watt sensitivity of 2.3 A/W. The current sensitivity of our detector is in good agreement with the results of other researchers. In particular, the ampere–watt sensitivity of the MSM detector in the Ag/ZnO contact system is 1.5 A/W [22], the maximum response of the MSM diode based on Ni interdigital contacts to ZnO at a wavelength of 385 nm corresponded to the ampere–watt sensitivity of the detector of 1.6 A/W, and the dark current was 1.04×10^{-6} A [23]. Note that the ampere–watt sensitivity of the investigated detector is slightly higher than the theoretical value due to the effect of internal photoamplification. This effect has also been observed by other authors [23–25].

An increase in the bias voltage also leads to an increase in the penetration depth of the electric field into the active volume of the detector; the response signal of the detector appears in the infrared region of the radiation spectrum due to the GaAs substrate (see Fig. 3). It has a sharp drop at a wavelength of 870 nm, which corresponds to the band gap of GaAs. The current sensitivity of the detector at a wavelength of 800 nm is 2.8 A/W. Thus, the investigated photodetector provides effective two-color detection of radiation in the visible and infrared part of the spectrum.

CONCLUSIONS

The results of experimental studies of a narrowband photodetector of the visible part of the spectrum based on an MSM diode are presented. The detector is implemented in the form of interdigitated Schottky MSM barrier contacts to the ZnCdSe/ZnSSe/GaAs heterobarrier structure. The detector provides a narrowband response at 460 nm (FWHM = 4.3 nm), a sharp drop in photosensitivity in the short-wavelength part of the response signal, high ampere–watt sensitivity (2.3 A/W), and low dark current (2×10^{-10} A).

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