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High spectral selectivity metal-semiconductor-metal photodetector

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Abstract
The results of experimental study of the metal-semiconductor-metal (MSM) photodiode based on ZnCdSe/ZnSSe/GaAs heterobarrier structure are presented. MSM-diode with 2.8 μm Ni-Au interdigitated Schottky barrier contacts, gaps between them of 3 μm, and total detector area of $100\times100\ \mu m^2$ have been fabricated and investigated. At a wavelength of 460 nm MSM-diode provides a high spectral selectivity with FWHM of spectral response 4.3 nm, high current sensitivity of 2.27 A/W and low dark current of 200 pA at 30 V bias. The spectral response of the MSM-detector was characterized under various bias conditions. A reduced Schottky barrier height model was adopted to explain the gain mechanism of the MSM-detector under illumination.

Keywords Metal-semiconductor-metal (MSM) diode · Photodetectors · Heterostructure · Dark current · Spectral response

1 Introduction

In the recent years narrow-band selective detectors of UV and visible radiation have been the subject of intense research and development (Ambacher 1998; Blank and Gol'dberg 2003; Averin et al. 2016; Qin et al. 2020). These detectors allow band-pass filtering of incoming signal just at the input of an optical registration system and are promising for use in industrial, scientific and military applications (communication, space and defense, medical instrumentation, environmental research, etc.) (Averin et al. 2016; Qin et al. 2020). Until recently, the detection of visible radiation has been accomplished exclusively with Si and GaAs detectors. The main drawback of these narrow-bandgap semiconductor detectors is device ageing due to exposure to radiation with an energy significantly exceeding the band gap of Si and GaAs (Metzger 1996; Vigue et al. 2001; Monroy et al. 2003). Another disadvantage of Si and GaAs detectors is that their maximum photosensitivity lies in the longer

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wavelength infrared region and for noise-immune narrow-band reception these detectors require the use of external filters (Vigue et al. 2001; Monroy et al. 2003; Qin et al. 2020). The modern methods of filtering optical radiation in UV and visible spectra are very diverse but their common weakness is a complication of the receiving system and reduced sensitivity (Sabnis 1999; Vigue et al. 2001; Monroy et al. 2003; Lee et al. 2014; Averin et al. 2016; Qin et al. 2020). Therefore, a photodetector with high spectral selectivity is highly desirable.

Nowadays wide-bandgap semiconductor materials and heterostructures have been intensively investigated as active layers for the development of UV and visible light detectors (Monroy et al. 2003). A wide-bandgap semiconductor is an important asset for fabrication of photodetectors since it allows one to realize low dark current and high device reliability under illumination with high-energy photons. In addition, by means of suitable heteroepitaxial layers, it is possible to construct a narrow-band detector response which will provide adequate filtering of the useful information signal and, thus, noise immunity of the optical receiving system. Various types of selective detectors based on wide-gap semiconductor materials and heterostructures were studied previously. A narrowband response with FWHM = 14 nm at 361 nm was reported for AlGaN / GaN MSM-detectors and explained by contribution of photoelectrons generated in two-dimensional electron gas channel (Huang et al. 2010). Yet more narrow peak of response with FWHM = 7 nm at ~370 nm was stated for the MSM-detectors on (Mg,Zn)O heterostructure (Zhang et al. 2011). A narrowband response with FWHM = 27 nm was realized on AlGaN / AlN MSM-photodiode at a wavelength of 240 nm (Averin et al. 2013). Some time ago we have announced the detecting properties of the MSM-diodes on low-dimensional heterostructures with ZnCdS quantum wells separated by ZnMgS and ZnS barrier layers (Averin et al. 2016). Detectors provided two color detection at the wavelengths of 350 and 450 nm with FWHM of spectral response 18 and 50 nm respectively. Quite recently the experimental results of photodetectors based on polymer perovskite layers have been presented (Qin et al. 2020). A narrow-band response with FWHM = 50 nm has been obtained on the MSM-diode with the opportunity to adjust the maximum detector sensitivity in the range of 680–710 nm.

In this work we investigate the option to reduce the width of the spectral response of the MSM-photodiode in the visible part of the spectrum while maintaining a high quantum efficiency of the detector. The detector is fabricated in the form of interdigitated metal-semiconductor-metal Schottky barrier contacts to the ZnCdSe / ZnSSe / GaAs heteroepitaxial structure and provides a narrowband response at a wavelength of 460 nm with FWHM of only4.3 nm.

2 Experimental results

Due to the high absorption coefficient in this region of the spectrum, the incoming optical radiation is absorbed in a narrow near-surface region of the semiconductor in use. For this reason, a surface-barrier planar diode structure based on double rectifying contacts in the metal-semiconductor-metal system was chosen as the basic photodiode structure. The MSM-diode was fabricated in the form of Ni-Au interdigitated Schottky barrier contacts to the ZnCdSe / ZnSSe heterobarrier structure grown by chemical vapor deposition from organometallic compounds (MOVPE) on a semi-insulating GaAs substrate 300 nm thick,

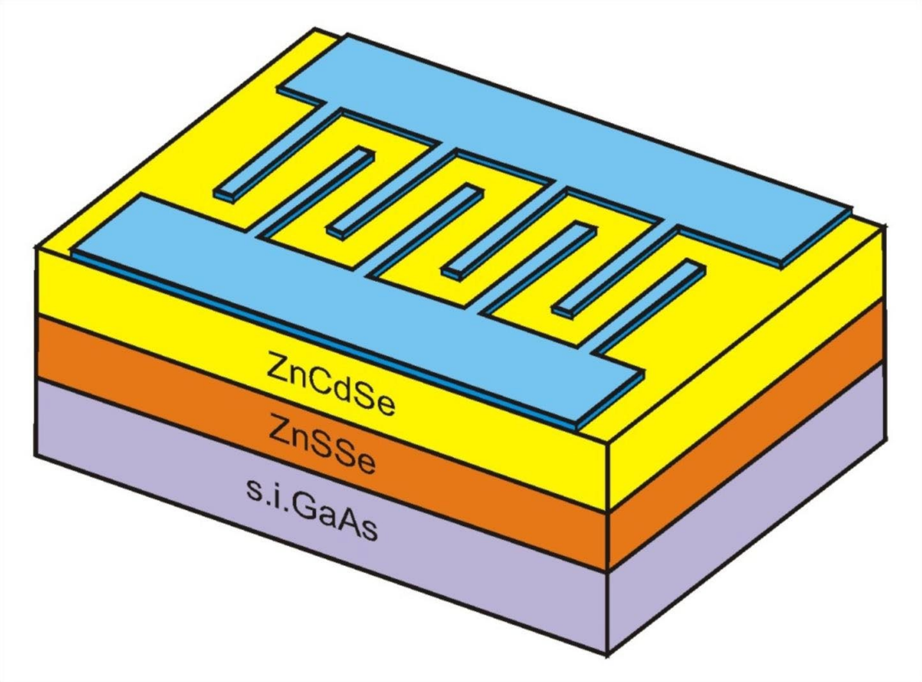

Fig. 1 Sequences of heteroepitaxial layers and interdigitated contacts of the MSM-diode

Fig. 1. The thickness of ZnCdSe layer was 130 nm and that of ZnSSe, 800 nm. A detailed description of heterostructure formation can be found elsewhere (Kuznetsov et al. 2002).

A film surface morphology was studied on the atomic force microscope (AFM) Smart SPM (AIST-NT). The surface of the heterostructure is dense and consists of small grains with relatively uniform distribution. Surface roughness of the film estimated from AFM-measurements on a square of 20×20 μm^2 was found to be RMS = 22 nm. To fabricate Schottky contacts of the MSM-diode, 90 nm thick Ni and 70 nm Au layers were deposited by means of electron beam evaporation and defined in the form of interdigitated metal contacts by photolithography and lift-off technique. The fingers of the MSM-diode are 2.8 µm wide, 100 µm long and with spacing of 3 µm. The photosensitive area of the MSM-detector is equal to 100×100 μm^2. Figure 2 shows a micrograph of a fragment of the MSM diode based on ZnCdSe / ZnSSe / GaAs heterobarrier structure.

The current-voltage characteristics of the fabricated MSM diodes have been investigated at room temperature on the parameter analyzer of semiconductor devices Agilent B 1500 A. They are shown in Fig. 3 at different polarities of bias voltage and exhibit low dark currents at sufficiently high voltages. At a bias voltage of 30 V the dark current is $2 \cdot 10^{-10}$ A which is comparable to the dark currents of the MSM-diodes based on the low-dimensional ZnCdS / ZnMgS / GaP heterostructure (Averin et al. 2015). The dark current of homoepitaxial ZnSe photodetectors was much higher, 5×10^{-9} A, and at lower bias of 4 V (Lin et al. 2005). Since both shot and 1/f noise are proportional to the amount of current flowing through the junction, the low dark current allows one to improve the signal-to-noise ratio of the detecting system.

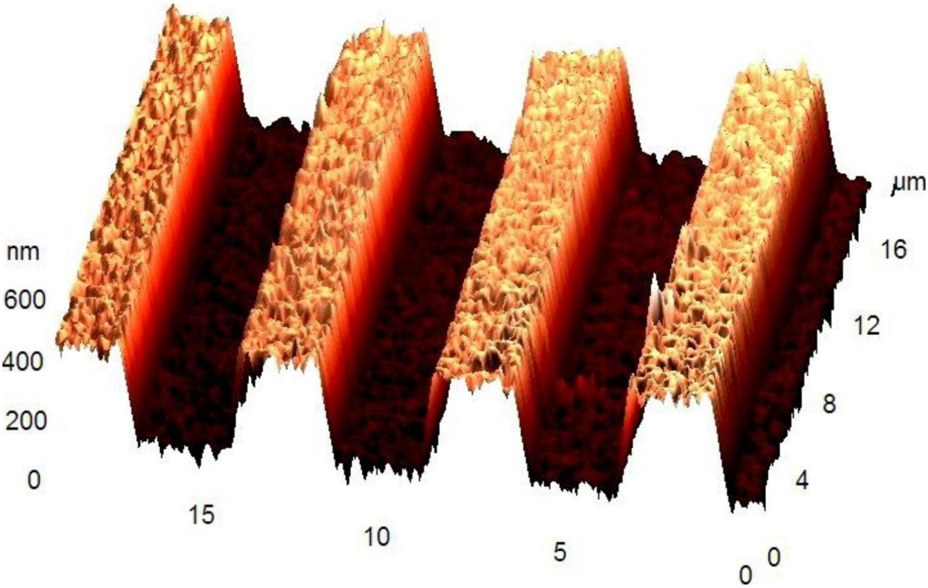

Fig. 2 AFM micrograph of a fragment of the MSM-photodetector based on ZnCdSe / ZnSSe / GaAs heterobarrier structure. The Ni-Au fingers are 100 µm long, 2.8 µm wide and with spacing of 3 µm

The dark current in diode structure depends on the height of the barrier contact. The MSM-detector consists essentially of two Schottky contacts connected back-to-back. When a bias is applied, one of the Schottky contacts is forward and the other is reverse biased. Even though the bias polarity has changed, only the reverse current–voltage characteristics of these Schottky contacts can be measured. Thus, in the MSM structures, one cannot use the conventional method of evaluation of Schottky contact parameters based on the forward portion of the I –V curve (Sze 1981; Schroder 1990).We have estimated a Schottky barrier height in a system of contacts of the MSM-diode in accordance with the method described in detail in (Averin et al. 2000). The analysis has shown that the Schottky barrier dark current is described in terms of thermionic emission. The barrier height in the investigated interdigitated system of contacts according to measurements and calculations is equal to 1.3 eV, and the junction ideality coefficient is $n = 1.2$. These parameters indicate the absence of a sufficiently thick intermediate oxide layer in the metal - semiconductor contact and high quality of the Schottky barriers of the MSM-diode under consideration. We also have to note a slight asymmetry of the MSM-diode *I-V* curves for positive and negative bias due to minute discrepancy between the barrier heights of two tandem connected Schottky barrier interdigitated contacts. This is presumably owing to different densities of states at the metal-semiconductor interface of two contiguous barrier contacts and inevitable growth defects leading to surface nonuniformities of the grown semiconductor structure and, as a consequence, to unequal effective areas of adjacent contacts. The breakdown voltages of the detectors are in the range of 120–130 V, demonstrating their persistence to possible surges in bias voltage under operation in real conditions.

The measurements of the photocurrent response were performed with Xe arc lamp whose radiation, passed through a monochromator, was chopped with frequency of 400 Hz and

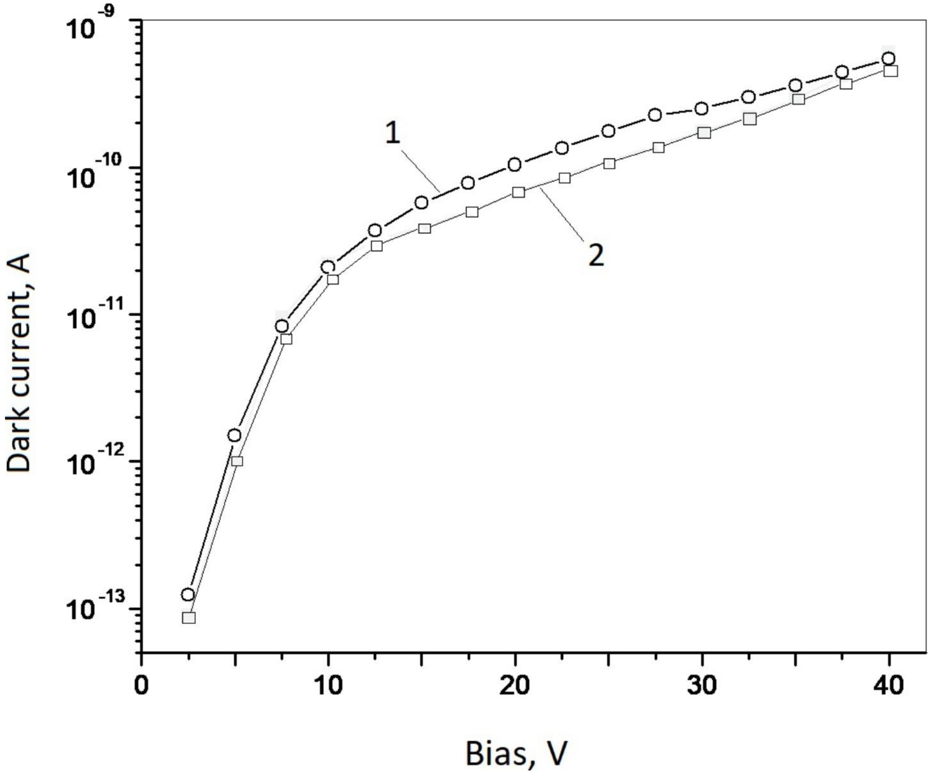

Fig. 3 Dark current of the MSM-heterophotodiode: 1–forward bias, 2–reverse bias

then focused on the investigated MSM-heterophotodiode with an optical lens system. The power illuminating the detector was estimated with a calibrated silicon photodiode. The resulting photocurrent was measured in ac-conditions with PAR-124 A lock-in amplifier. The responsivity of the detector was derived as a ratio of the measured current signal from the MSM-heterophotodiode to the optical power striking the detector at appropriate wavelength. Figure 4 shows the photoresponse of the MSM-heterophotodiode as a function of wavelength at various biases. The detector provides sufficiently narrowband response. At the wavelength of 460 nm the full width at half maximum of detector response (FWHM) is 4.3 nm and is the smallest known and published in the literature for the detectors of radiation in the visible part of the spectrum. It was shown before (Sou et al. 1999; Monroy et al. 2003) that ZnSSe photodetectors provide a sharp decrease in sensitivity in the long-wavelength part of the response signal (red detector boundary). This is also observed in our experiment, Fig. 4. For 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, light is absorbed closer to the surface of heterostructure in thin ZnCdSe layer. As a result, the concentration of photogenerated electrons and holes in this region is very high, this substantially decreases the lifetime of charge carriers and increases the probability of surface and bulk recombination (Vigue et al. 2001; Jandow et al. 2010; Redaelli et al. 2014). Further explanation of the narrowband detector response comes after study of newly fabricated

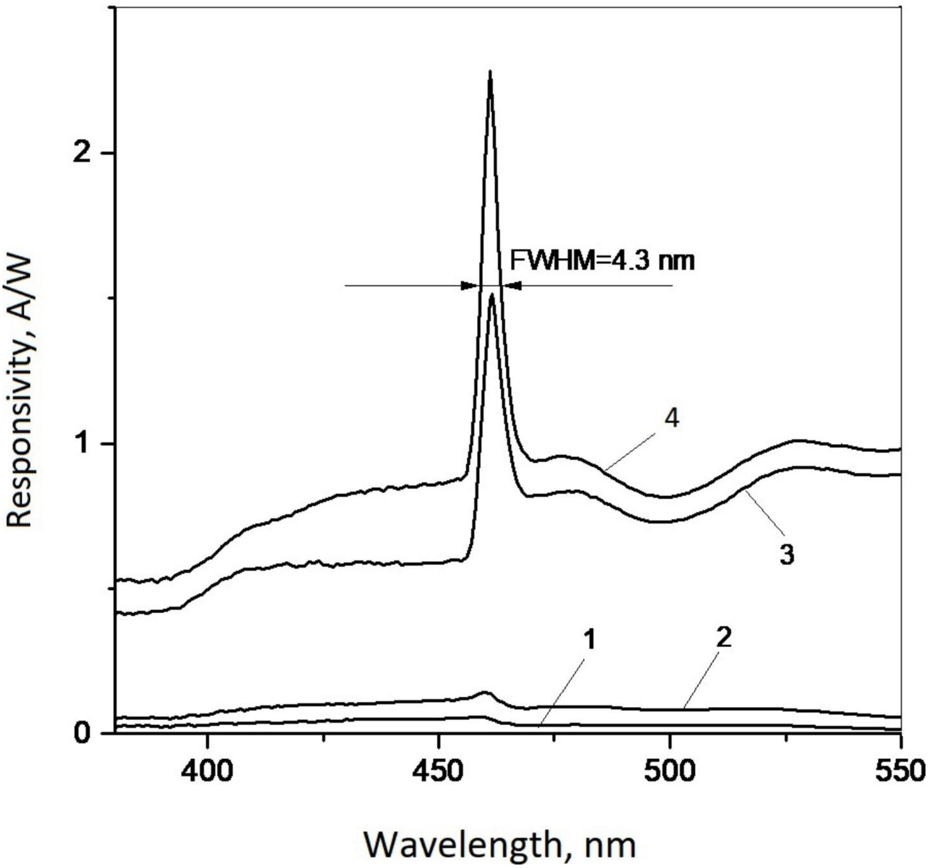

Fig. 4 Spectrum of the photoresponse signal of the MSM-detector: bias 5 (*1*), 10 (*2*), 20 (*3*), and 30 V (*4*)

MSM-diodes of the same contact geometry, but without upper ZnCdSe layer. The active layer of this detector consists of epitaxial ZnSSe, 530 nm thick. The investigation shows that this detector provides a broadband response to an optical signal in the spectral range of 330–465 nm. Thus, other things being equal, the upper ZnCdSe layer plays the main role in the photoresponse of the MSM-photodiode based on ZnCdSe / ZnSSe heterostructure at high photon energies of incoming signal. The carriers recombine in this layer long before they reach the interdigitated contacts of the MSM-heterophotodiode.

Figure 5 shows the responsivity of the MSM-heterophotodiode as a function of the bias voltage. The photocurrent first rises with increasing bias and then becomes saturated. Two-dimensional simulation of the MSM-diode (Averine et al. 1996) shows that for a gap between interdigitated contacts of 3 μm and bias voltages < 10 V detector operates under condition of partial depletion of the active interelectrode region. This is confirmed by a significant decrease in the detector response signal in the bias range of 5–10 V, Fig. 5. An increase of the bias leads to the expansion of the depleted region of the reverse-biased Schottky con-

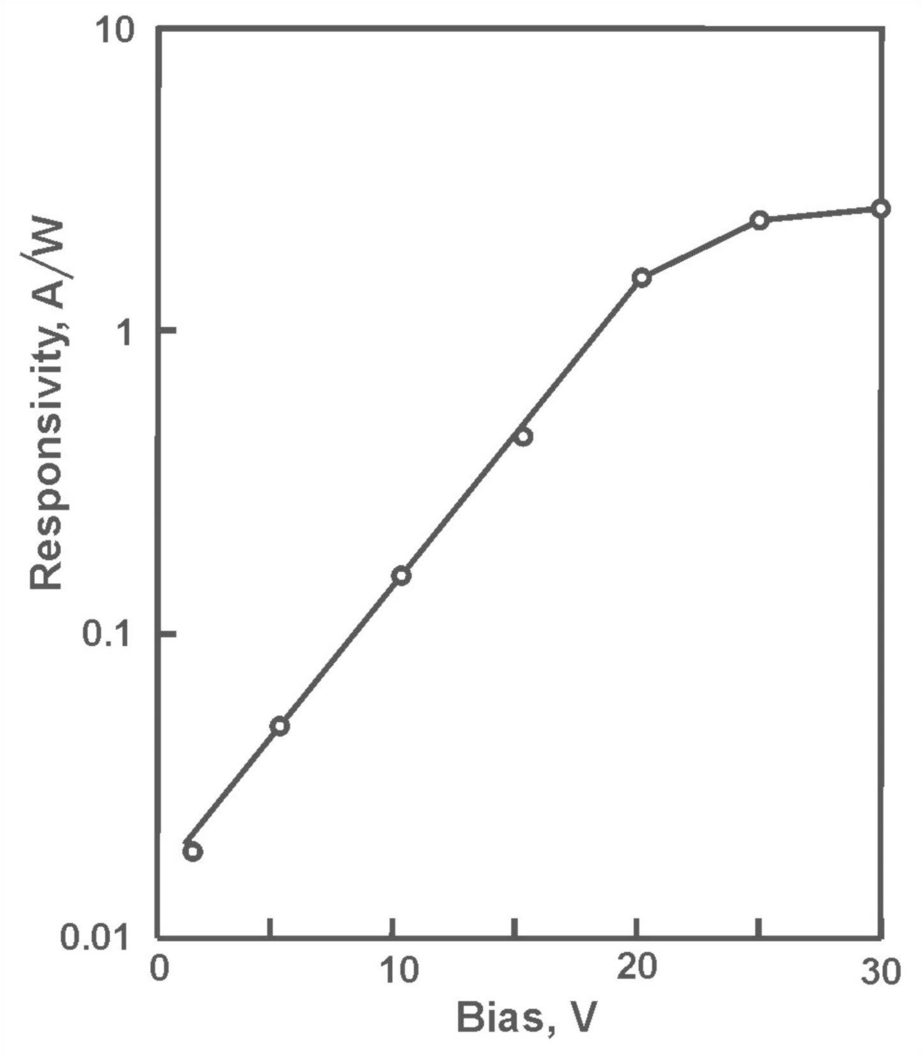

Fig. 5 Responsivity of the MSM-heterophotodiode as a function of bias voltage

tact, and peak responsivity at 460 nm rapidly increases from 0.05 A/W at 5 V to 1.5 A/W at 20 V, as shown in Fig. 5, thus leading to an increase in the detector EQE from 13.5% up to 404%. The voltage at which the photocurrent starts to saturate corresponds to the flat band condition (S.M. Sze et al. 1971). This condition is estimated by one-dimensional depletion equation (S.M. Sze et al. 1971):

$$V_{FB} = \frac{qN_d t^2}{2\varepsilon_s}, \tag{1}$$

where t is interelectrode spacing, N_d and ε_s is doping and dielectric constant of underlying semiconductor material. For N_d =2 10^{15} cm^{-3}, t =3 µm, ε_s=9.31, then V_{FB} =20 V and is in good agreement with our experiment.

At a bias voltage of 30 V the peak responsivity of the MSM-diode is 2.27 A/W and taking into account that 50% of detector area is shadowed with interdigitated contacts, the detector internal quantum efficiency is 1224%. An internal QE higher than 100% indicates that photocurrent gain is involved. The photocurrent gain can be described in terms of the barrier lowering due to the charge traps at the ZnCdSe / ZnSSe heterointerface (Sciuto et al. 2007; Zhang et al. 2011). Under illumination, Schottky barrier exhibits hole trapping in the reverse-bias junction that shrinks the depletion region, lowers built-in potential and effective barrier height, causing more carriers crossing the barrier and thus enlarge the photocurrent. The trapped charges are known to increase with applied bias, producing an enhancement in the barrier lowering (Sciuto et al. 2007). Thus the optical response increases with external bias. Assuming all the photons are absorbed by the semiconductor between the interdigitated contacts, we have calculated that the total gain of the detector is 6.14. The current sensitivity of our detector is in good agreement with the results of other researchers. For example, the current sensitivity of the MSM-detector with Ag/ZnO Schottky barrier interdigitated contact system is 1.5 A/W and the leakage current is about 1 nA at a bias of 5 V (Liang et al. 2001). The maximum response of the MSM-diode based on Ni interdigitated contacts to ZnO at a wavelength of 385 nm is corresponded to the current sensitivity of the detector 1.6 A/W, and the dark current is 1.04 10^{-6} A (Jandow et al. 2010). A maximum spectral photo response of 1.8 A/W was realized in the MSM-photodetectors based on (Mg,Zn)O heterostructures at the wavelength of 369 nm (Zhang, et al. 2011). Recently, planar metal-insulator-semiconductor-metal photodetectors fabricated on a silicon-on-insulator substrate with n-type silicon device layer have demonstrated record responsivity for silicon detectors of 1.77 A/W at the wavelength of 405 nm (Mikelashvili, et al. 2019).

Though the MSM-detector is potentially high speed device, we have to note that the trapped holes may be the main reason for the long decay time of detector and thus slow the detector response down to tens of nanoseconds. This may have a concern for some applications. Detailed studies on the transient behavior of these detectors are underway in our laboratory and the results will be presented elsewhere.

3 Conclusion

We have experimentally established extremely narrow spectral response of the MSM-detector based on ZnCdSe / ZnSSe / GaAs heterostructure. The peak of photoresponsivity with FWHM = 4.3 nm and current sensitivity of detector 2.27 A/W was measured at a wavelength of 460 nm. The spectral response of the MSM-detector was characterized under various bias conditions. An increase of the photocurrent was observed, and the internal quantum efficiency higher than unity was measured involving the presence of internal gain. The model of minority carrier (holes) trapping at ZnCdSe / ZnSSe -interface has been adopted to explain the observed internal gain mechanism in the MSM-detector due to Schottky barrier height lowering under illumination. The narrow-band response of the detector may provide effective filtering of the useful incoming signal and thus the noise immunity of the optical informational and measuring system.

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Data availability (data sharing not applicable to this article)

Code availability not applicable

Declarations

Conflicts of interest/Competing interests not applicable

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