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NOVEL RADIO SYSTEMS AND ELEMENTS

Two-Color Photodetector for the Visible Spectral Range Based on ZnSe/ZnS/GaAs Bragg Reflector

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Abstract—Effect of the ZnSe/ZnS/GaAs distributed Bragg reflector (DBR) on the parameters of the spectral response of a photodiode based on rectifying contacts in the metal–semiconductor–metal (MSM) system is studied. The calculated photoreflection spectra of the ZnSe/ZnS/GaAs heterostructure are in good agreement with the experimental data. It is shown that the MSM diode provides two-color response of the photodetector at wavelengths of 420 and 472 nm, a sharp decrease in the photosensitivity in the long-wavelength part of the response signal, high quantum efficiency (53%), and low dark current (5×10^{-10} A). It is demonstrated that the narrow-band two-color response of the detector can be tuned to the desired wavelength using appropriate selection of the parameters of the heterostructure that forms that Bragg reflector.

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INTRODUCTION

Development of bandpass detectors for spectral intervals in the visible and near-IR spectral ranges is a topical problem of modern optoelectronics [1]. Such detectors make it possible to filter out optical signals at the entrance of the data system, so that such a system becomes simpler and more efficient. Selective detection in two and more spectral intervals of optical radiation simplifies analysis of the object under study, since the wavelength dependence of emissivity can be determined and selective recognition of the object can be implemented [2]. It is expedient to develop multicolor photodetectors the sensitivity of which can be tuned to specified fragment of the radiation spectrum. Multicolor photodetectors are needed for several practical applications in military systems, image visualization, environmental monitoring, communication systems, etc. [3–6].

Silicon and arsenide–gallium detectors are normally employed in a spectral interval of 0.6–0.9 μm. The photosensitivity region of such detectors is relatively wide, and external filters are needed for selective response at the desired wavelengths [7–9]. Thus, the receiving system becomes more complicated and its sensitivity decreases.

Fabrication of nanoheterostructures of wide-bandgap semiconductors is the key point in the development of efficient selectively sensitive photodetectors. We have recently studied detection properties of low-dimensional heterostructures with quantum wells ZnCdS separated with ZnMgS buffer layers that provide two-color detection of the UV radiation at wavelengths of 350 and 450 nm [10]. In this work, we study metal–semiconductor–metal (MSM) photodiode structures based on ZnSe/ZnS periodic nanosized heterostructures that form a distributed Bragg reflector (DBR).

Bragg reflectors have been used as mirrors for reflection of optical radiation from lower regions of planar photodiodes to the near-surface region of the strong field of diode (i.e., for an increase in the quantum efficiency of the photodetector) [11, 12]. We have analyzed a possibility for an increase in the reflection coefficient of the Bragg reflector based on the ZnSe/ZnS periodic heterostructure grown on the GaAs substrate due to optimization of the growth process [13]. In this work, we employ the DBR to obtain narrow-band two-color response of the MSM diode. The spectral characteristic of the MSM diode provides detection at two wavelengths in the visible spectral range using a single photodiode. Variation in the parameters of the ZnSe/ZnS heteroepitaxial layers can be used to change the peak position of the reflected signal of the Bragg reflector and, hence, the spectral response of the MSM heterophotodiode in a relatively wide wavelength interval in the visible spectral range. As distinct from the Si and GaAs detectors, the proposed detectors based on the heteroepitaxial layers of ZnSe/ZnS wide-bandgap semiconductor compounds are potentially stable against high-energy irradiation and bias voltages [8].

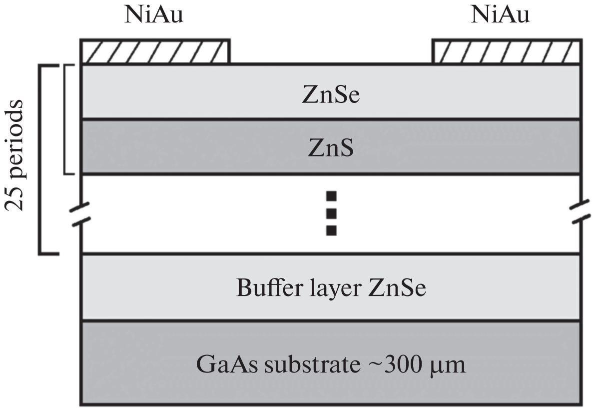

Fig. 1. Layers of the heteroepitaxial structure that forms the Bragg reflector of the MSM photodiode.

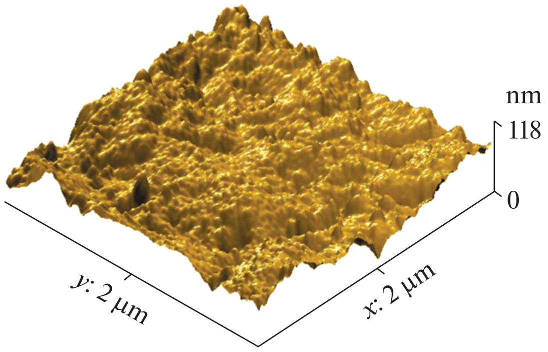

Fig. 2. Microphotograph of the surface of the ZnSe/ZnS structure obtained with the aid of an AIST-NT SmartSPM AFM.

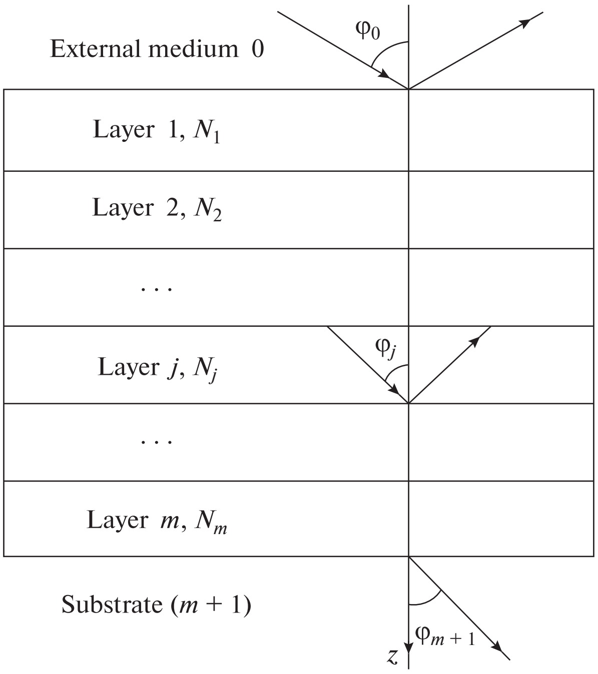

Fig. 3. Reflection and transmission of the multilayer structure.

EXPERIMENTAL RESULTS

Surface-barrier planar diodes based on rectifying junction in the MSM system (MSM diodes) [13] are used in the study. Structural and technological simplicity is an important feature of such a detector that employs a semiconductor with a certain type of conductivity. We study the effect of the Bragg reflector on the spectral sensitivity of the MSM detector.

The DBR was grown with the aid of the MOVPE method using sequential deposition of 25 pairs of quarter-wavelength ZnSe and Zn layers on a semi-insulating (100) GaAs substrate (Fig. 1). Deposition is performed in a horizontal quartz reactor at a hydrogen pressure that is close to atmospheric pressure and a temperature of 450°C using diethylzinc, dimethylselenide, and diethylsulfide as reagents (see [14] for details). The quality of the growth surface is monitored using atomic force microscopy with the aid of an AIST-NT SmartSPM device. Relatively smooth surface of the heterostructure consists of uniformly distributed grains (Fig. 2). The measurements show that the mean-square roughness of the surface at an area of 20 × 20 μm is 20.2 nm. Contact photolithography is used to form interdigitated contacts of the MSM detector on the grown structures. The widths of and distances between the contacts are identical (2.8 μm), and the active area of the detector is 100 × 100 μm^2.

For calculation of the reflection spectrum of the ZnSe/ZnS)$_{25}$ZnSe/GaAs multilayer heteroepitaxial structure, we use the method of 2 × 2 matrices [15]. The method is based on the linearity of the Maxwell equations that describe the propagation of light and the fact that the continuity of the tangential components of the electric and magnetic fields of optical wave at the interface of two isotropic media can be described using the linear 2 × 2 matrix transformation. We assume that each layer of the structure (Fig. 3) represents linear homogeneous isotropic medium that is describe using complex refractive index $N(\lambda)$. Optical properties remain unchanged inside each layer and exhibit stepwise changes at the interfaces of the layers.

Scattering matrix **S** can be used to establish relationship of the complex amplitudes of electric field E in the external medium and substrate in the planes adjacent to the interfaces of the structure layers: $E(z_{1-0}) = \mathbf{S}E(z_{(m+1)+0})$. Such a matrix can be represented as a product of matrices of interfaces **I** and layers **L**:

$$\mathbf{S} = \mathbf{I}_{01} \times \mathbf{L}_1 \times \mathbf{I}_{12} \times \mathbf{L}_2 \ldots \mathbf{I}_{(j-1)j} \times \mathbf{L}_j \ldots \mathbf{L}_m \times \mathbf{I}_{m(m+1)}. \quad (1)$$

Matrix of interface **I** is represented in terms of the Fresnel coefficients of reflection and transmission for the interface, which depend on the complex refractive indices of the neighboring media ($N_{(j-1)}$ and N_j),

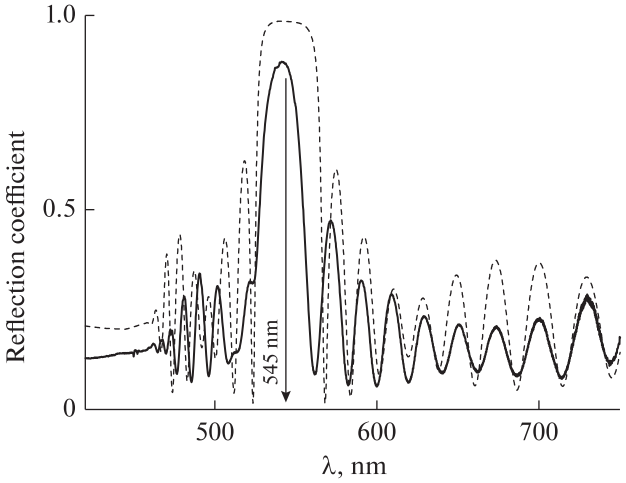

Fig. 4. (Dashed line) Calculated and (solid line) experimental reflection spectra of the $(ZnSe/ZnS)_{25}ZnSe/GaAs$ heteroepitaxial structure.

angle of incidence at the given point, and polarization (parallel (*p*) or perpendicular (*s*) to the plane of incidence). Matrix of layer **L** is represented in terms of phase shift β of plane wave λ having passed through layer with thickness *d* along the direction that makes angle φ with perpendicular to the interfaces (*z* axis):

$$\beta = (2\pi dN/\lambda)\cos(\varphi). \quad (2)$$

Reflectance *R* and transmittance *T* of layered structure are represented in terms of elements of scattering matrix **S**:

$$R = (\mathbf{S}_{21}/\mathbf{S}_{11}), \quad T = (1/\mathbf{S}_{21}). \quad (3)$$

In accordance with the experimental conditions for the measurement of the reflection (configuration of the beams and light source), we calculate reflection spectra at zero angle of incidence and assume that the contributions of the *p* and *s* polarizations to the reflection are identical.

To compare the calculated and experimental results, we grew several DBRs with reflection maxima (rejection band of the DBR) at different wavelengths and measured the reflection spectra. Figure 4 shows the calculated and experimental reflection spectra of the grown heterostructure for the system of layers air → $(ZnSe/ZnS)_{25}$ → ZnSe → GaAs. In the calculations, the thicknesses of the ZnS and ZnSe layers in the heterostructure are 57 and 51.5 nm, respectively, and the thickness of the ZnSe lower buffer layer is 567 nm. For such a system of layers, Fig. 4 shows good agreement of the calculated and experimental curves of photoreflection.

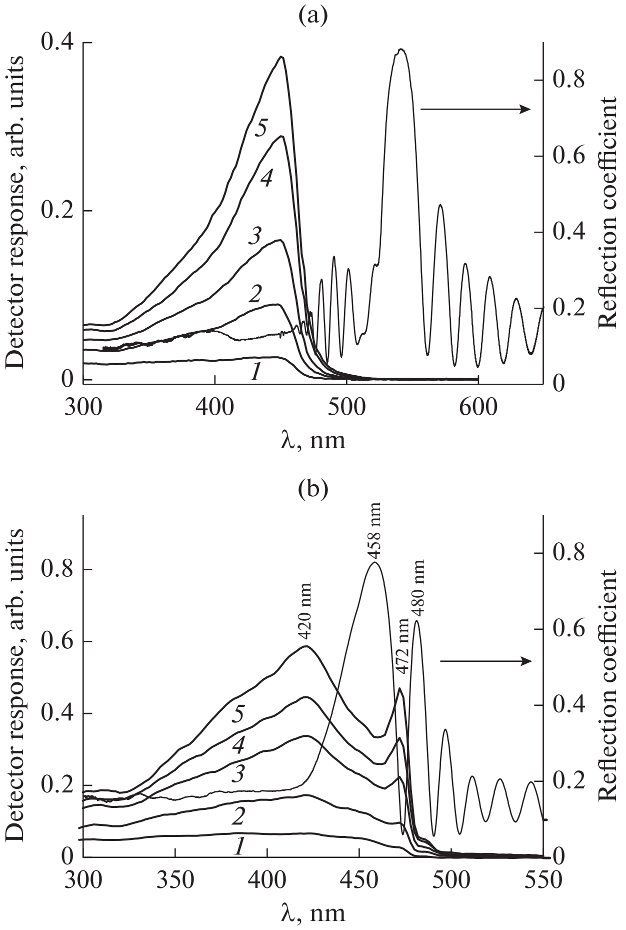

Fig. 5. Spectrum of the photoreflection signal of the $(ZnSe/ZnS)_{25}/GaAs$ periodical heterostructure and the spectral response of the MSM diode based on such a structure for (a) bias voltages of (*1*) 20, (*2*) 40, (*3*) 60, (*4*) 80, and (*5*) 90 V and the reflection peak of the Bragg reflector at a wavelength of 545 nm that insignificantly affects the spectral response of the MSM diode and (b) bias voltages of (*1*) 30, (*2*) 50, (*3*) 70, (*4*) 80, and (*5*) 90 V and the Bragg reflector that provides narrow-band two-color photodetection for the MSM diode.

Figure 5a presents the experimental reflection spectrum of the heterostructure with the above parameters and the spectral response of the MSM diode based on such a structure. The main peak of the DBR reflection at a wavelength of 545 nm insignificantly affects the spectral response of the MSM diode that is almost identical to the spectral response of the MSM diode fabricated on a relatively thick (200 nm) ZnSe epitaxial layer grown on semi-insulating GaAs [9]. Based on such a result, we change the parameters of the epitaxial layers in the $ZnSe/ZnS)_{25}ZnSe/GaAs$ heterostructure that forms the Bragg reflector. For the blue shift of the DBR reflection peak, we use the calculated results and grow 25 pairs of the ZnS and ZnSe layers with thicknesses of 46.7 and 39 nm, respectively, at a thickness of the ZnSe buffer layer of 430 nm. Figure 5b shows that such changes lead to the blue shift of the main peak of the photoreflection signal and significant changes of the spectral response of the MSM photodiode. DBR reflectance peaked at a wavelength of 458 nm is located almost at the center of the photosensitivity spectrum of the MSM diode that is obtained in the absence of the effect of the Bragg reflector (Figs. 5a and 5b). Thus, the response signal of the MSM diode with such a DBR exhibits two photosensitivity peaks at wavelengths of 420 and 472 nm. Note that the reflection signal of the Bragg reflector peaked at a wavelength of 480 nm (first side peak) leads to a steeper decrease in the photosensitivity of the MSM diode in the long-wavelength part of the response signal. The DBR works as a built-in notch filter for the radiation that is incident on the photodetector. Such a structure efficiently reflects the radiation at the selected wavelength (458 nm) and provides spectral selection of the received optical signal. Thus, we obtain a narrow-band two-color MSM detector based on the $(ZnSe/ZnS)_{25}ZnSe/GaAs$ periodic heterostructure (Fig. 5b). The long-wavelength response of the MSM diode under study is in good agreement with the threshold energy of direct optical transitions in ZnSe. The narrow-band two-color response of the photodetector can be tuned to the desired wavelength in an interval of 350–480 nm using changes of the parameters of the heterostructure.

At a bias voltage of 90 V, the maximum photoresponse of the MSM diode at a wavelength of 420 nm corresponds to an ampere–watt sensitivity of 0.18 A/W and an external quantum efficiency of EQE = 53%. The dark current of the detector (5×10^{-10} A at a bias voltage of 40 V) is comparable with the dark currents of the MSM diodes based on the ZnCdS/ZnMgS/GaP low-dimensional heterostructure with the same configuration of contacts [10] and substantially less than the dark current of the MSM diode based on ZnSe (5×10^{-9} A at a bias voltage of 4 V) [16]. The sensitivity of the proposed detector can be compared with the published results. An ampere–watt sensitivity of 0.1 A/W at a wavelength of 460 nm is reached in [8, 9] for the ZnSe diodes with semitransparent Ni/Au contacts with the Schottky barrier. The maximum sensitivity of the ZnSe MSM diode is 0.128 A/W at a wavelength of 448 nm and the quantum efficiency is 38% in [16]. The sensitivity (0.4 A/W in a wavelength interval of 350–450 nm) and dark current (about 4×10^{-10} A at a bias voltage of 40 V) of the ZnSTeSe heterobarrier MSM diode of [17] are in good agreement with the results of this work. Note relatively narrow transmission bands of the detector: FWHMs of 15 and 50 nm at central wavelengths of 472 and 420 nm, respectively.

CONCLUSIONS

We have studied a new type of photodiode structures (MSM photodiodes with DBR based on the ZnSe/ZnS periodic heterostructure). The DBR serves as a built-in notch filter for the radiation incident on the photodetector. Such a reflector efficiently reflects optical radiation at the desired wavelength (458 nm) and provides spectral selection of the input radiation. Thus, we obtain narrow-band two-color response of the MSM detector with photosensitivity peaks at wavelengths of 420 and 472 nm. The MSM detector exhibits a sharp decrease in the photosensitivity in the long-wavelength part of the response signal, high quantum efficiency (53%), and low dark current (5×10^{-10} A). The narrow-band two-color response of the detector can be tuned to the desired wavelength using appropriate changes of the parameters of the heterostructure layers that form the Bragg reflector.

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