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MSM-photodetector with ZnSe/ZnS/GaAs Bragg reflector

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Abstract
The effect of a ZnSe/ZnS/GaAs distributed Bragg reflector on the spectral response of a metal–semiconductor–metal (MSM)-diode is investigated. Good agreement is obtained between the calculated and experimental reflection spectra of the ZnSe/ZnS/GaAs heterostructure forming a distributed Bragg reflector in the MSM-diode. The MSM-detector provides a two-color response at 420 and 472 nm, a sharp decrease in photosensitivity in the long-wave part of the response signal, high quantum efficiency of 53%, and low dark current of 5×10^{-10} A. The two-color response of the detector can be adjusted to the desired wavelength by appropriately selecting the heterostructure parameters.

Keywords Metal–semiconductor–metal (MSM) diode · Infrared detectors · Heterostructure · Bragg reflector · Dark current · Spectral response

1 Introduction

The development of selectively sensitive narrow-band photodetectors for visible and near-infrared is a topical problem of modern optoelectronics (Blank and Gol'dberg 2003). These detectors allow band-pass filtering of incoming signal at the input of an optical detection system. This fact greatly simplifies the detection system and increases its potential. The spectral response of conventional silicon and gallium arsenide detectors is observed in a sufficiently wide range in visible and near infrared and does not satisfy the requirement of selectivity (Rogalski 2009; Steenbergen et al. 2010; Lin et al. 2005). Selective reception by these detectors requires the use of external filters (Rogalski 2009). This leads to complexity of the receiving system and significantly reduces its sensitivity.

Multicolor optical sensing at specific wavelengths is an area of active research and essential for a variety of practical applications in military science, spectroscopy, image visualization, environmental monitoring, remote control, optical communication, etc. (Choi 1997; Majumdar et al. 2002; Steenbergen et al. 2010; Konstantanos and Sargent 2010). Selective detection of two or more separate regions of emission spectra significantly simplifies the analysis of the observed object, since in this case one can determine the

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wavelength dependent emissivity of the object and thus realize selective identifying and recognition of the object (Rogalski 2009).

The development of wide-bandgap semiconductor heterostructures is a key point in creating efficient selectively sensitive detectors in this spectral region. Recently, we have investigated the metal–semiconductor–metal (MSM) photodetectors based on periodic heterostructures with ZnCdS quantum wells separated by ZnMgS and ZnS barrier layers (Averin et al. 2015). These detectors provide two-color detection of UV radiation at the wavelengths of 350 and 450 nm. In this work we investigate a new type of photodiode structure—MSM-photodiode based on a periodic low-dimensional ZnSe/ZnS heterostructure forming a distributed Bragg reflector. Bragg reflector has already been used as a back mirror to reflect the incoming light from the bottom of a planar photodiode into a near-surface region of the diode, that is, to increase the quantum efficiency of the detector (Collin et al. 2011; Gallo et al. 2013). Previously, we also studied the possibility of increasing the reflectivity of a distributed Bragg reflector based on a periodic ZnS/ZnSe heterostructure grown on a GaAs substrate by optimizing the growth process (Kuznetsov et al. 2002). In the present work, a distributed Bragg reflector (DBR) does not increase the detector quantum efficiency but for the first time is used to form a two-color response of the MSM-diode. The spectral response of the MSM-diode with DBR provides detection of two separately standing wavelengths of visible light by a single photodiode. We show that, by changing the parameters of the ZnSe/ZnS heteroepitaxial layers, it is possible to shift the position of the maximum of DBR reflection signal and thus to change the spectral response of the MSM-diode in a fairly wide wavelength range of the visible part of spectrum. In contrast to Si and GaAs detectors, the developed detector is based on heteroepitaxial layers of wide-bandgap semiconductor compounds and thus is potentially resistant to detrimental effects of high-energy radiation and high bias voltages (Monroy et al. 2003).

2 Experimental results

The metal–semiconductor–metal (MSM) diode structure has been chosen as a basic structure for investigation. The MSM-diode has been widely used in recent years because of its fabrication simplicity, fast response, low dark current and direct compatibility with modern high-speed integrated circuitry (Ito and Wada 1986; Averine et al. 2001; Chang et al. 2002; Averin et al. 2015). Our goal is to study the effect of distributed Bragg reflector on the spectral response of the MSM-detector based on it.

A distributed Bragg reflector was grown by successive deposition of twenty five pairs of quarter-wave ZnSe/ZnS layers on a semiinsulating (100) GaAs substrate, and forms the absorption layer of the MSM-diode, Fig. 1. The deposition process was carried out by metal organic vapor phase epitaxy (MOVPE) at 450 °C in a horizontal quartz reactor at near atmospheric pressure of hydrogen. Diethylzinc, dimethylselenide and diethylsulphide were used as a precursors. A detailed description of DBR formation can be found in (Kuznetsov et al. 2002). The film surface morphology was studied on Smart SPM (AIST-NT) atomic force microscope (AFM). The surface of the heterostructure is dense and consists of small grains with relatively uniform distribution. The surface roughness of the film, estimated from the AFM measurements on a square of $20 \times 20\ \mu m^2$, was found to be $RMS = 20.2$ nm. To fabricate Schottky contacts of the MSM-diode, we deposited 90-nm thick Ni and 70-nm thick Au layers by means of electron beam evaporation and defined contacts in a form of interdigital metal electrodes by photolithography. The fingers of the

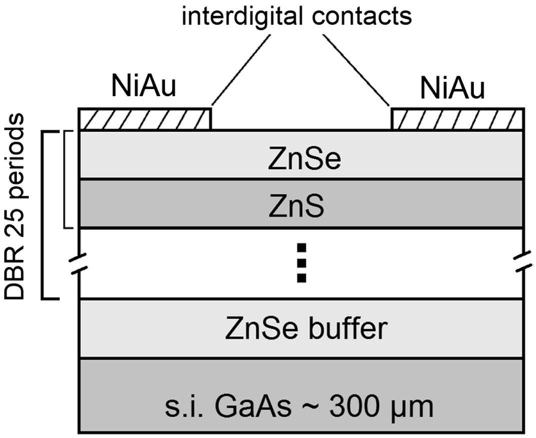

Fig. 1 The sequence of heteroepitaxial layers forming a distributed Bragg reflector of the MSM-diode

MSM-diode are 3 μm wide, 100 μm long and are spaced 3 μm apart. The photosensitive area of the MSM-detector is equal to 100 × 100 μm^2. In our analysis the interdigital electrodes of the MSM-diode are considered to be opaque; a finger gap is much larger than a wavelength of incoming light, therefore, the diffraction effects can be neglected.

To calculate the reflection spectrum of the multilayer heteroepitaxial structure $(ZnSe/ZnS)_{25}ZnSe/GaAs$, we applied the 2 × 2 matrix method (Azzam and Bashara 1977). Maxwell equations describing the propagation of light are linear, and the continuity of tangential components of electric and magnetic fields at the boundary between two isotropic media can be described by a linear 2 × 2 matrix transformation. It is assumed that each layer of the structure (Fig. 2) is a linear, homogeneous and isotropic medium described by the complex refractive index N_j, and its thickness is d_j. The optical

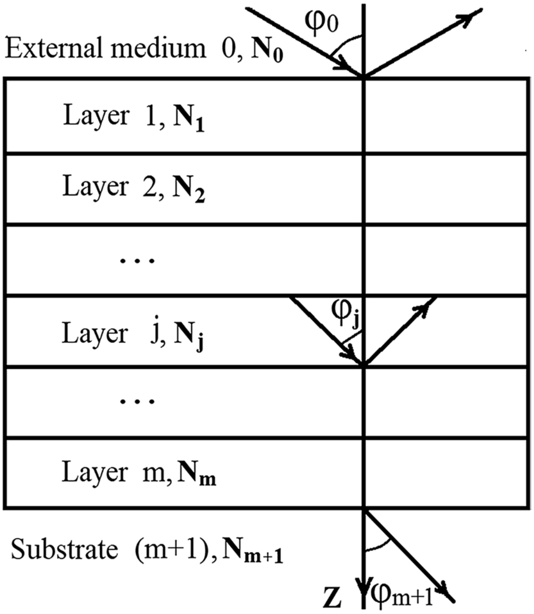

Fig. 2 Reflection and transmission of a plane wave by a multilayer structure

properties are uniform within each layer of the structure and change abruptly at the interfaces between layers.

The scattering matrix S connects the complex amplitudes of the electric field E in external medium and in the substrate in the planes directly adjacent to the interfaces of the structure layers, $E(z_{1-0}) = S \cdot E(z_{(m+1)+0})$. It can be represented as a product of the interface and layers matrices I and L:

$$S = I_{01} \times L_1 \times I_{12} \times L_2 \ldots \; I_{(j-1)j} \times L_j \ldots L_m \times I_{m(m+1)} \tag{1}$$

The interface matrix I is expressed in terms of the Fresnel reflection and transmission coefficients of the interface, which, in turn, are determined by the complex refractive indices of the adjacent media ($N_{(j-1)}$ and N_j), the angle of incidence at a given point, and the polarization of light (parallel or perpendicular to the plane of incidence). The layer matrix L is expressed through a phase shift β of a plane wave λ passing through a layer of thickness d at an angle φ to the z axis,

$$\beta = (2\pi dN/\lambda)\cos(\varphi). \tag{2}$$

The overall reflection and transmission coefficients of the layered structure are expressed in terms of the elements of the scattering matrix S:

$$R = (S_{21}/S_{11}), \quad T = (1/S_{21}). \tag{3}$$

In accordance with the experimental conditions, the angle of incidence for the calculation of reflection spectra was taken to be zero, and the contributions of p- and s-polarizations to the reflection were assumed to be the same.

To check the agreement between the calculated and experimental data, we prepared several DBRs with a reflection maximum at specific wavelengths and measured their reflection spectra. The calculated and experimental reflection spectra of the system $>(ZnSe/ZnS)_{25} \rightarrow ZnSe\ buffer \rightarrow GaAs$ are presented in Fig. 3 for one of the grown heterostructures. In the calculation, the thickness of each single layer of ZnSe and ZnS forming the heterostructure was set equal to 57 nm and 51.5 nm, respectively, and the thickness of the lower buffer layer ZnSe was taken to be 567 nm. One can see quite

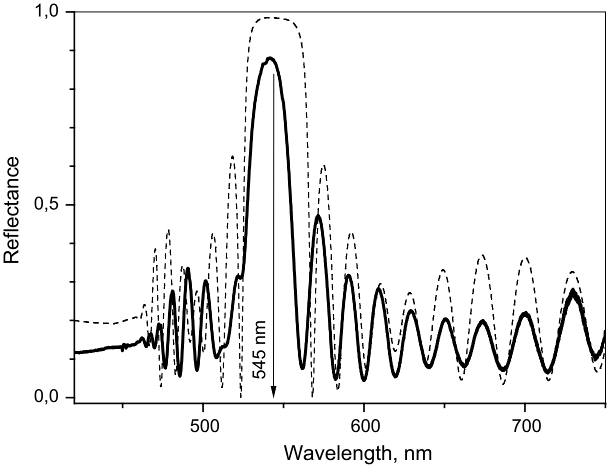

Fig. 3 Calculated (dashed) and experimental reflection spectra of the heteroepitaxial structure $(ZnSe/ZnS)_{25}ZnSe/GaAs$

a good agreement between the calculated and experimental photoreflection curves in Fig. 3.

Figure 4 shows the experimental reflection spectrum of the heterostructure with the above parameters along with the spectral response of the MSM-diode which was fabricated on this heterostructure. One can see that the main reflection peak of the DBR at a wavelength of 545 nm does not take effect on the spectral response of the MSM-diode, which in this case hardly differs from the spectral response of the diodes fabricated on rather thick (200 nm) epitaxial layers of ZnSe grown on a semi-insulating GaAs substrate (Vigue et al. 2000; Monroy et al. 2003; Lin et al. 2005). Therefore, we have changed the parameters of the epitaxial layers of the $(ZnSe/ZnS)_{25}ZnSe/GaAs$ heterostructure forming the Bragg reflector. To shift the main peak of DBR reflection into the blue region of the spectrum, in accordance with the calculations, 25 pairs of 46.7-nm (ZnSe) and 39-nm (ZnS) layers were grown on the 430-nm ZnSe buffer. This allowed us not only to shift the main peak of the DBR photoreflection signal towards shorter wavelength but also to significantly change the spectral response of the MSM-photodiode, Fig. 5.

Now the maximum reflection of the DBR occurs at a wavelength of 458 nm and almost in the middle of the photosensitivity spectrum of the MSM-diode without the effective influence of the Bragg reflector on the diode spectral response (Fig. 4). As a result, two photosensitivity peaks at the wavelengths of 420 and 472 nm are formed in the response signal of the MSM-diode, Fig. 5. At the same time, the first side peak of DBR reflection at a wavelength of 480 nm leads to an increase in the rolloff of the photosensitivity of the MSM-diode in the long-wave part of the detector response. The distributed Bragg reflector acts as a built-in notch filter of the input radiation incident on the photodetector. It effectively reflects radiation at a selected wavelength (458 nm) and provides spectral selectivity of the incoming optical signal. As a result, a two-color response of the MSM-detector based on a periodic heterostructure $(ZnSe/ZnS)_{25}ZnSe/GaAs$ is formed, Fig. 5.

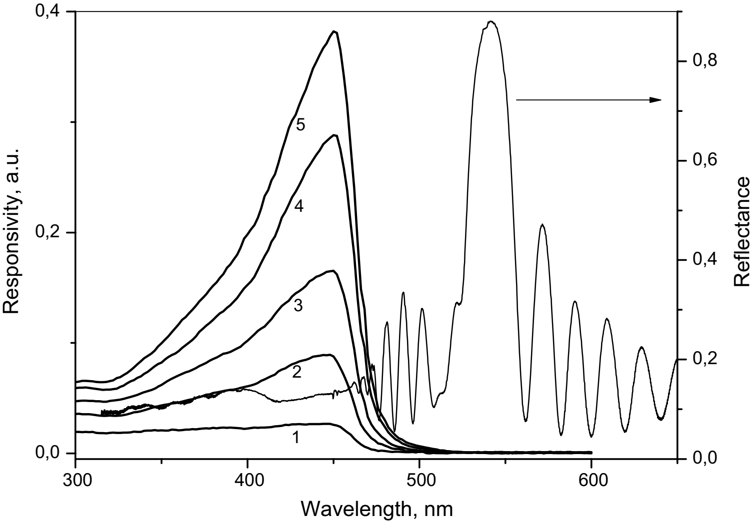

Fig. 4 Reflection spectrum of periodic heterostructure $(ZnSe/ZnS)_{25}ZnSe/GaAs$ and the spectral response of an MSM-diode based on it. Bias voltage: 1–20, 2–40, 3–60, 4–80, 5–90 V. The peak of reflection is at the wavelength of 545 nm and does not affect the spectral response of the MSM-diode

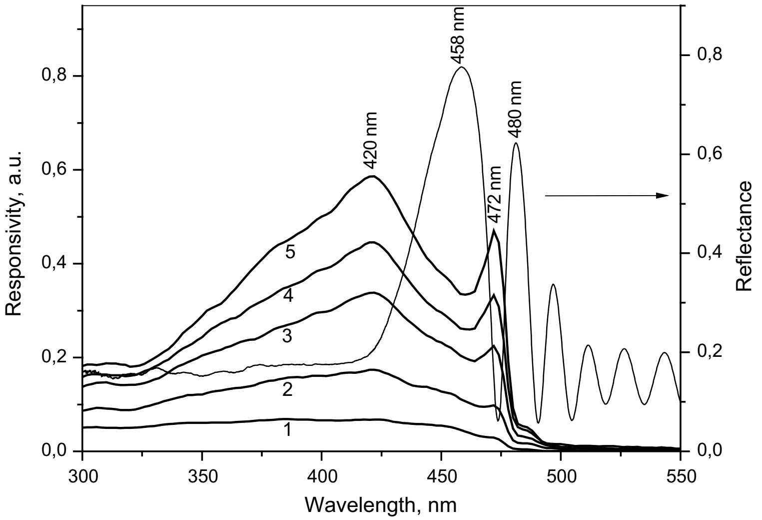

Fig. 5 Reflection spectrum of periodic heterostructure $(ZnSe/ZnS)_{25}ZnSe/GaAs$ and the spectral response of the MSM-photodiode based on it. Bias voltage: 1–30, 2–50, 3–70, 4–80, 5–90 V. Bragg reflector provides two-color photodetection of the MSM-photodiode

The long-wavelength response of the MSM-diode under study is in good agreement with the threshold energy of direct optical transitions in ZnSe, and, by proper selection of the heterostructure parameters, one can adjust the narrow-band two-color photodetector response to the desired emission wavelength in the range of 350–480 nm. The maximum photoresponse signal of the MSM-diode at a wavelength of 420 nm and a bias voltage of 90 V corresponds to detector current sensitivity of 0.18 A/W and an external quantum efficiency of EQE = 53%. The dark current of the detector at room temperature is 5×10^{-10} A at bias voltage 40 V, which is comparable with the dark currents of the MSM-diodes based on low-dimensional ZnCdS/ZnMgS/GaP heterostructures (Averin et al. 2015) and is significantly less than the dark current 5×10^{-9} A of the MSM-diode on ZnSe at bias of 4 V (Lin et al. 2005).

We can compare the sensitivity of our detector with the results of other research groups. ZnSe diodes with Schottky barrier semi-transparent Ni/Au contacts demonstrate a current sensitivity of ~ 0.1 A/W at a wavelength of 460 nm (Monroy et al. 2003; Vigue et al. 2000). The current sensitivity of ZnSe MSM-diode was 0.128 A/W at 448 nm, and the quantum efficiency was equal to 38% (Lin et al. 2005). The current sensitivity of a heterobarrier ZnSTeSe MSM-diode in the range of wavelengths 350–450 nm is equal to 0.4 A/W, and the dark current is ~ 4×10^{-10} A at a bias voltage of 40 V (Chang et al. 2002) which is in good agreement with our results.

The detector is rather narrowband. It provides a bandwidth of 15 nm and 50 nm (at the half-maximum level) at the wavelengths of 472 and 420 nm, respectively.

3 Conclusions

We have investigated a new type of photodiode structure—an MSM photodiode with a distributed Bragg reflector based on a periodic ZnSe/ZnS/GaAs heterostructure. The DBR forms a built-in notch filter for the input light radiation incident on the photodetector, which effectively reflects light at a selected wavelength (458 nm) and provides a spectral selection of the input light signal. As a result, a two-color response of the MSM-detector with photosensitivity peaks at 420 and 472 nm is formed. The MSM-detector demonstrates a sharp decrease in photosensitivity in the long-wave part of the response, high quantum efficiency of 53% and low dark current of 5×10^{-10} A. The two-color response of the detector can be adjusted to the desired wavelength by appropriately selecting the parameters of the heterostructure layers forming the Bragg reflector.

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