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RADIATION DETECTION

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High-speed, efficient metal – semiconductor – metal photodetectors*

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Abstract. **Design principles and the fabrication technique of highly efficient, high-speed photodetectors based on MSM nanostructures are developed. To efficiently confine light in the region of the strong field as well as to decrease light losses due to reflection from the diode contacts, use is made of a nanoscale interdigital diffraction grating and a multilayer Bragg grating. Measurements of the reflection coefficients and the quantum efficiency for a multilayer structure are in good agreement with theoretical estimates. A record-high quantum efficiency (QE = 46 %) is obtained for high speed MSM photodetectors. The detector has a high spectral selectivity ($\Delta\lambda_{1/2}$ = 17 nm) at a wavelength of 800 nm. Taking into account the diode capacitance and the drift time of photogenerated carriers, the performance of the detectors under study is ~ 500 GHz. The low level of the dark current density in the structures under study (j = 1 pA μm^{-2}) makes it possible to realise on their basis highly sensitive, high-speed selective detectors of optical radiation.**

Keywords: *photodetector, nanostructures, MSM diode, quantum efficiency.*

High-speed photodetectors are very promising for creating broadband fibreoptic systems, are of interest for generating terahertz radiation by means of optical mixing of signals from two lasers on a photodiode, and finally, they are necessary for carrying out many scientific experiments. Significant progress in detecting ultrashort optical pulses has been achieved recently mainly due to a decrease in the drift distances with a simultaneous decrease in parasitic capacitances of semiconductor diode structures [1 – 4]. The main high-speed photodiode structures are the known pin diodes [4] and the recently available photodiode structures based on metal – semiconductor – metal contacts (MSM diodes) [1 – 3]. To this end, because the radiation absorption depth in known semiconductor materials is ~1 μm, a decrease in the interelectrode distance below this value with the attempt to increase the detector speed of response leads to a rapid decrease in the quantum efficiency of a pin diode and to an increase in the capacitance for both types of structures. Reducing the capacitance requires a decrease in the detector area. The area being the same, the MSM diode has a smaller capacitance than the pin diode [5], and hence it possesses a better potential to increase the detector speed of response.

The MSM-diode structure is rather simple [2]. An interdigital system of contacts is built on the surface of a semiconductor material grown on a semi-insulating substrate by the photolithography method. Falling photons with the energy larger than the energy gap width of the semiconductor material produce electron – hole pairs in the region between the contacts within the absorption depth, these pairs being separated by the electric field of the diode and collected on the interdigital contacts. Speed and efficiency of charge carrier collection determine the detector speed of response and its efficiency. As was noted above, an important feature is the extremely low capacitance of the MSM diode, which is four times smaller than the capacitance of the pin diode with the same area [5].

MSM diodes with the contact dimensions and spacing between them of the order of 100 and even 25 nm have been already manufactured and studied [1]. To achieve a balanced effect of the carrier drift time and the structure capacitance on the detector response time, the active area of such structures measures 1×1 μm. In this case, along with the difficulties in focusing received radiation on a small area of the detector and with the technological difficulties in manufacturing MSM nanostructures, there arises another problem related to the small depth of the efficient penetration of the electric field in such structures [6]. The electric field, rather strong in the near-surface region of the structure, rapidly drops in submicron structures while moving deep into the diode. Therefore, most charge carriers are generated in the weak field region of the MSM diode and their drift velocities are small. Note also that the mean free path of the carrier drift to the contacts in MSM nanostructures is determined not so much by the contact gap as by the radiation absorption depth. This leads to the signal pulling of the detector pulse response and to low sensitivity. Light reflection from interdigital contacts also reduces the MSM-diode efficiency, and despite very small characteristic dimensions, the cutoff frequencies of such detectors amount to 300 – 500 GHz with the quantum efficiency of only 3 % – 5 % [1, 6].

The detector speed of response can be increased in the heterobarrier structure [6]. The presence of the heterobarrier in the active region of the diode allows one to block efficiently electrons and holes generated in the region of a weak electric field, to reduce the charge carrier drift and to increase signifi-

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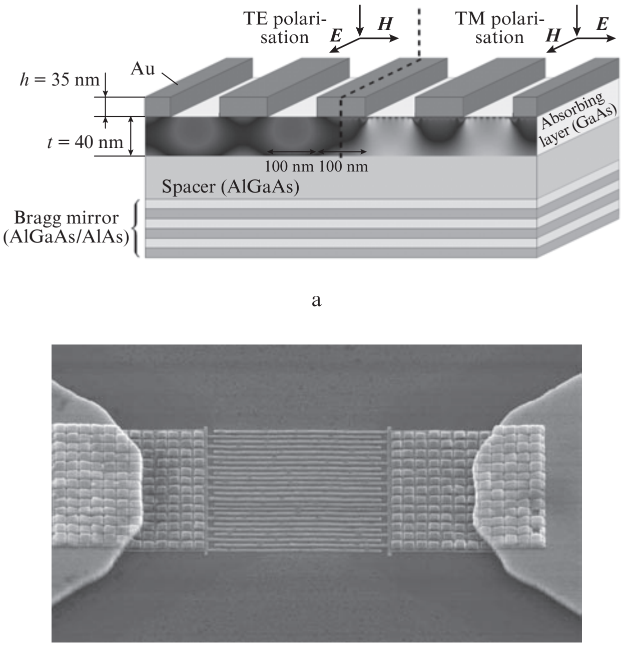
cantly the detector speed of response. However, in this case, a substantial part of charge carriers is uselessly lost; therefore, the quantum efficiency of the heterobarrier MSM diode is small, i.e. ~8%. To achieve high speed and high quantum efficiency in the photodetector, it is necessary to search for the new ways of radiation confinement in the near surface region of the MSM diode and of decreasing the light reflection losses due to the opacity of the diode interdigital contacts.

In this paper, we present the results of experimental investigations of the photodiode MSM structure by using a nanoscale interdigital contact grating making it possible to confine efficiently radiation in the strong field of the diode and to decrease light losses due to reflection from the contacts. This provides a significant increase in the photodetector efficiency while preserving its high-speed response.

Figure 1 presents the MSM-photodetector structure. The interdigital system of MSM-diode contacts forms a partially reflecting, optically transparent diffraction grating, which is the upper mirror of the Fabry–Perot resonator. The lower resonator mirror is made in the form of a multilayer Bragg mirror (24 periods of AlAs/$Al_{0.2}Ga_{0.8}As$ quarter-wave layers), while the resonator cavity is formed by a thin absorbing layer (GaAs, 40 nm) located on the surface of the optically transparent spacer ($Al_{0.35}Ga_{0.65}As$, 30 nm). The structure was grown on a semi-insulating GaAs substrate by the molecular-beam epitaxy method.



a

b

Figure 1. Photodiode structure and spatial distribution of the electric field intensity in the active volume of the MSM photodetector for TE- and TM-polarised radiation (a) and photograph of the photodetector obtained by the scanning electronic microscope (b).

The interdigital system of the MSM diode was formed by a grating with contacts 35 nm in height and was made by depositing Au (27 nm) by an electron beam with the following lift-off in trichloroethylene. The Ti underlayer (2–5 nm) provides better adhesion of contacts to GaAs. The contact width and the spacing between them was 100 nm, the active region of the detectors measured 3×3, 5×5, and 10×10 μm. This geometry, as shown in investigations, ensures the resonance behaviour of the structure at a wavelength of 800 nm. Thus, the wavelength of the received radiation is eight times greater than the characteristic dimensions of the grating. Figure 1b shows the photograph of the MSM detector obtained by a scanning electronic microscope.

We should also say a few words about the optical transparency (at some wavelength) of the diffraction grating, which represents an interdigital system of the MSM-diode contacts. Recently, the authors of paper [7], studying the optical properties of gratings based on submicron cylindrical holes in metal films, found that at the wavelengths far exceeding the grating period, the transparency of such structures can be orders of magnitude larger than that expected from the standard aperture theory. Such unusual optical properties of a two-dimensional periodic structure with the characteristic dimensions tenfold smaller than the light wavelength result from excitation of plasmons on the surface of the periodic structure. Excitation of horizontal surface plasmons leads to a significant increase in the field intensity on the horizontal surfaces of the metal film, which, in turn, results in efficient resonance tunnelling of radiation through the grating with the dimensions smaller than the wavelength [8]. These observations initiated a number of theoretical papers devoted to the interaction of radiation with nanometer periodic structures [8–10] and lead to the possibility of producing new photonic devices. The surface resonance properties in periodic structures have already found applications in optoelectronic devices; in particular, they are used in radiation devices [11] and tunable filters [12]. We were first to use the property of surface plasmons to transmit efficiently radiation through the grating with dimensions smaller than the wavelength in order to couple the optical signal into the active region of the MSM diode (Fig. 1). The results of the electromagnetic calculation of the entire structure performed by using the modal method [9, 10] showed that for the selected detector parameters the diode structure under study is very promising for receiving TE-polarised radiation. In this case, charge carriers are generated in a narrow near-surface region with high electric field strength between the electrodes of the interdigital contact system.

Figure 2 shows the reflection and absorption spectra for a nanometer contact grating made of Au with a Ti underlayer (2 nm) for TE-polarised incident light. Both the calculations and experiments show that despite the presence of metal inter-

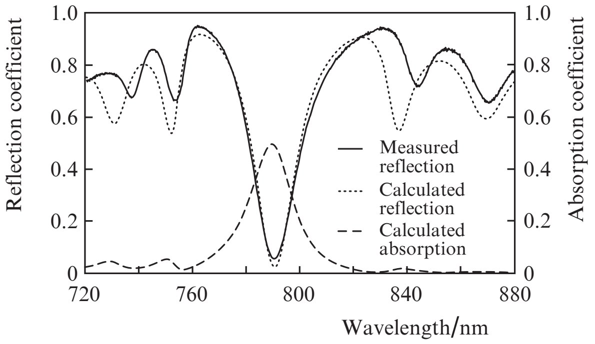


Figure 2. Reflection and absorption spectra for a nanometer contact grating made of Au (30 nm) with a Ti underlayer (2 nm) for TE-polarised incident light.

digital contacts in the MSM diode, only a small portion of incident radiation at 790 nm is reflected from the detector surface, while 50% of light falls into the bulk of the structure and is absorbed in the 40-nm-thick active GaAs layer. Note that calculated and experimental reflection coefficients for the nanostructures under study are in good agreement.

To make the detector highly sensitive, it is necessary to fabricate high quality Schottky contacts. The current–voltage characteristics of the MSM diodes were studied on the Agilent 4156C precision semiconductor parameter analyser. The typical level of the dark current in the diode with the 5×5-μm active region was equal to 10 pA at the 1-V bias voltage and to less than 50 pA at 2 V (Fig. 3). Such structures are characterised by a decrease in the barrier height due to the strong electric field in the contact region (Schottky effect). Earlier we showed the possibility of determining the main parameters of the Schottky contact directly in the MSM microstructure [13]. Taking into account the reduction of the barrier height due to the field and tunnelling, we found that in the contacts under study the barrier height is $\Phi = 0.6$ eV, the saturation current is $I_s = 2.5\times10^{-11}$ A, and the ideality coefficient is equal to 1.05. These parameters indicate the high quality of the Schottky barrier in the manufactured contacts and the absence of the intermediate oxide layer at the Ti–GaAs interface. The low dark current density in the structures under study allows one to realise on their basis sensitive detectors of optical radiation.

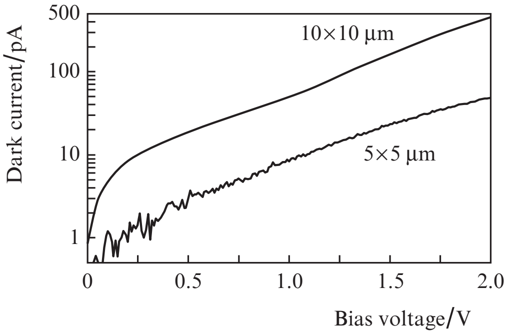


Figure 3. Current–voltage characteristic of the studied photodiode structures with the dimensions of the active region measuring 5×5 and 10×10 μm.

The spectral sensitivity of the MSM diodes was measured with a tunable laser source (Ti:sapphire laser) and a Jvon-Jobin spectrometer. The spectral dependence of all the optical components and the laser was measured with a Newport 818-ST calibrated detector. Laser radiation was focused on the active region of the MSM detector with the help of the objective and recorded with a CCD camera. The power of light incident on the diodes being tested was varied by using the calibrated filters and measured with a reference detector. Figure 4 presents the spectral selectivity of the quantum efficiency of the studied MSM detector in the wavelength range from 760 to 820 nm, in agreement with the calculated data. The maximum external quantum efficiency of the detector for the 20-nW power of the incident TE-polarised wave was 46% ($\lambda = 790$ nm). This is more than an order of magnitude larger than the efficiency of a standard MSM photodiode with the same geometry and is record high for high-speed radiation photodetectors. When the optical signal power is increased, the detector efficiency decreases due to screening the dark electric field of the diode by the space charge of photogenerated holes [14].

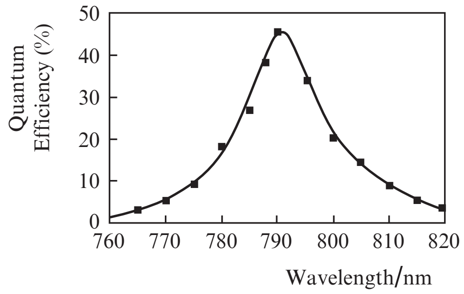


Figure 4. Dependence of the quantum efficiency of the MSM photodiode on the radiation wavelength.

The generated charge carriers in the diode under study are efficiently collected due to radiation confinement in the near-surface region of the strong electric field of the MSM detector. Because the mean free path of the charge carrier is ~50 nm and the diode capacitance is ~8 fF, this makes it possible to obtain the ~500-GHz cutoff frequency for the MSM detector. The detector is rather narrowband (Fig. 4): for the maximum sensitivity at a wavelength of 790 nm, the FWHM transmission bandwidth is 17 nm. The wavelength of the maximum detector sensitivity can be varied by changing the geometry of the interdigital contacts in the MSM diode. The selective and sensitive detector allows special filtration of received optical radiation used in WDM systems [15]. The detector also proves convenient in open systems transmitting optical data signals because it does not require the use of special filters reducing the potential of the system.

Therefore, we have studied a novel type of MSM-photodiode structures with the characteristic dimensions much smaller than the wavelength of received optical radiation. The nanoscale interdigital contact grating together with the Bragg mirror are used both to decrease the light losses during the light reflection from diode structure contacts and to confine efficiently radiation in the strong field of the MSM diode. Excitation of horizontal surface plasmons leads to efficient transmission of light through the contact grating whose dimensions are smaller than the wavelength. This ensures efficient collection of photogenerated charge carriers, resonance sensitivity, and high-speed response of the MSM diode. At the resonance wavelength, the quantum efficiency of the developed MSM diode is an order of magnitude larger than that of a standard MSM photodetector with the same geometry. The low dark current density in the structures under study allows one to realise on their basis sensitive selective detectors of optical radiation.

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