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Experimental investigation of Schottky barrier diodes as nonlinear elements in 800-nm-wavelength region

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ABSTRACT We report the results of experimental investigations of nonlinear properties of InP, GaAs and InGaAs Schottky barrier diodes (SBD) in the near-infrared range (λ ≈ 800 nm). The results of our previous and present work show that SBD have a unique broadband spectral sensitivity (from the millimeter to the visible range). As video detectors the GaAs-SBD proved to be the most sensitive among the other diodes, but they concede to the InP-SBD as frequency mixer–multipliers in spite of their higher cut-off frequency. The higher efficiency of the InP-SBD in a mixer–multiplier mode is supposedly connected with the bulk nonlinearity properties of indium phosphide, lower noise and lower time constants, characterizing the charge-carrier energy growth in an electric field and its relaxation. We found that the optimal operation conditions for SBD suppose not only the optimal electric regime (applying a defined bias or a defined radiation source power) but also the optimal mutual orientation of a laser radiation polarization, a contacting wire (playing the role of an antenna) and a laser beam.

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1 Introduction

A constant interest in use of Schottky barrier diodes (SBD) in different systems as high-speed photodetectors is caused by unique properties of these nonlinear elements, such as broadband spectral sensitivity, high response speed and room-temperature operation [1, 2]. Due to these features SBD are being successfully used for frequency conversion in high-resolution spectroscopy, optical frequency metrology and synthesis and development of optical frequency standards.

Recent investigations of Schottky barrier diodes are directed to development of new structures, including planar, based on different semiconductor materials, and also to discover physical processes defining the speed of the diodes and their ability to work in different spectral ranges. Success in these directions makes possible a practical realization of measuring and research apparatus using the high efficiency of SBD as frequency converters in the wavelength range from the millimeter to the visible.

In this paper we report an investigation of detector and mixer–multiplier properties of the InP, GaAs and InGaAs Schottky barrier diodes with a honeycomb structure of contacts [3] in the near-infrared range (λ ≈ 800 nm). Anode diameters of the tested diodes were in the range of 1.2–1.5 micron; barrier heights were 0.3–0.4 V for the InP-SBD and the InGaAs-SBD and 0.8–0.9 V for the GaAs-SBD. Detailed structure and parameters of the diodes can be found elsewhere [4]. We also made an attempt to analyze mechanisms responsible for the high speed of the diodes and their ability to work effectively in different spectral ranges taking into account results of this and previous work.

2 Experimental setup and results

The experimental setup for SBD investigation is depicted in Fig. 1. Diodes were set in a specially designed mixer–multiplier mount [5] with a built-in low-noise radiofrequency (rf) preamplifier and a stabilized bias-current supply. The bias current could be set either positive or negative and could be varied in a range from −400 μA to 5 mA. A Kerr-lens-mode-locked femtosecond Ti : sapphire laser was used as a laser radiation source. The laser output spectrum was centered at λ ≈ 800 nm with FWHM of ∼ 5 THz (the pulse duration was ∼ 100 fs), the pulse-repetition rate was ∼ 100 MHz and the output power was up to 200 mW. The laser radiation was focussed onto the SBD contact area by a lens. The setup also included a millimeter-range tunable Gunn-diode oscillator (GDO). Millimeter (MM) radiation was coupled onto a SBD antenna (contacting wire) through a waveguide-microstrip line. When frequency mixing occurred, a rf beat signal generated in the SBD was preamplified and led to a rf spectrum analyzer (SA). Frequency conversion can be described by

$$||\nu_i - \nu_j| - n f_g| = f_b, \qquad (1)$$

where ν_i and ν_j are frequencies of the Ti : sapphire laser spectrum, f_g is the GDO frequency, n is the GDO harmonic number and f_b is the beat-signal frequency (1–10 MHz), and where the signal-to-noise ratio (S/N) was measured by a spectrum analyzer. Note that the observed signal is a superposition of the beats between the microwave and all the spectral lines of the laser comb separated by $n f_g + f_b$.

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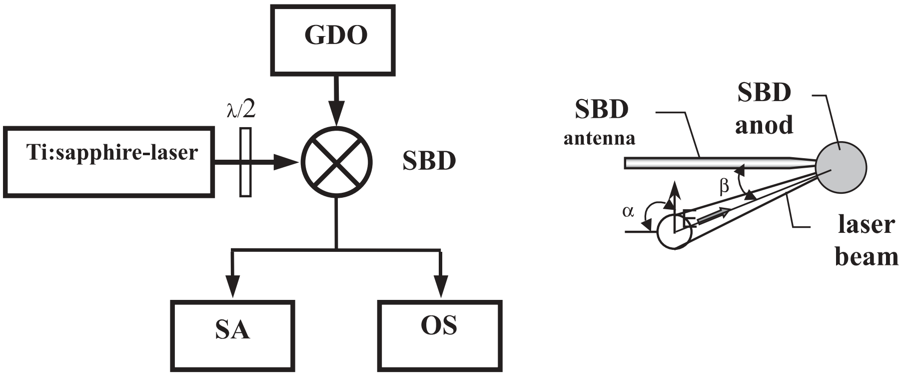

FIGURE 1 Experimental setup for SBD investigation. GDO – Gunn-diode oscillator, SA – rf spectrum analyzer, OS – oscilloscope, $\lambda/2$ – half-wave plate. A fragment on the *right* shows how angles α and β were defined: α – an angle between the laser polarization plane E and the beam incidence plane, β – an angle between the antenna and the laser beam axes

In a detector mode, laser radiation was modulated by a chopper (not shown in the figure) and the detected video signal was monitored on an oscilloscope (OS). The volt–watt sensitivity, defined as a ratio of the detected video-signal amplitude (voltage) to the power of the incident radiation, was used as a criterion of SBD detecting efficiency.

Antenna properties of SBD, such as antenna directivity and polarization sensitivity, were studied. For investigation of antenna directivity the diode mount could be rotated by an angle of β between the antenna and the laser beam axes (right-hand fragment of Fig. 1). A half-wave plate was used to rotate the laser polarization plane with respect to the beam incidence plane (a plane of SBD antenna and laser beam) by an angle of α; $\alpha = 0$ corresponds to coincidence of those planes.

Experimental investigation of the diodes was carried out in two steps. In the first step we studied detector properties of SBD and found the optimal experimental conditions (the optimal laser and millimeter-radiation coupling and the optimal bias current) for obtaining the detected video signal of the maximal amplitude. In the second step we investigated mixer–multiplier properties of SBD. Here we also optimized experimental conditions to get the maximal S/N and the maximal mixing order. It is worth mentioning that conditions for the optimal mixer–multiplier performance were usually different from those for the optimal detector performance. This effect is similar to the difference between experimental conditions when SBD have the maximal tangential sensitivity (a detector mode) and the minimal conversion losses (a mixer mode) [6].

From three to ten diodes of each type were investigated. A deviation of amplitudes of video signals and beat signals for different samples was in the range of 10%–15% at the same contact characteristics and other similar conditions. A coupling of the laser radiation onto the SBD contact was optimized in the following way: given a size of the SBD anode and the laser wavelength, the focal distance of a coupling lens was chosen to match the diameters of the laser beam in the focal point and the anode. This allowed us to decrease a loss of laser power significantly. Detected video signals were measured at the load of 1 MΩ, beat signals at 50 Ω.

As a recap of the results of our previous SBD investigation in the submillimeter (SMM) and the mid-IR ranges [2, 4], we mention here a significant difference in behavior of the diodes based on different semiconductors. The InP-SBD proved to be the most effective frequency mixer–multipliers in the mid IR, while in the SMM range the GaAs diodes were more efficient. As detectors the GaAs-SBD were more sensitive than the others in both ranges.

Spectral dependence of the volt–watt sensitivity of the GaAs- and the InP-SBD is shown in Fig. 2. Here the data from our previous work on SBD were also used [2, 4, 7]. The video signals were detected at the positive (direct) diode bias. The volt–watt sensitivity proved to be independent of the incident power in the range of tens of μW to hundreds of mW. A comparison of detector properties of the investigated diodes shows that in the range of 0.8 μm, as well as in the other ones, the GaAs-SBD are the most effective: they allowed us to obtain video signals of the highest amplitude. The video-signals ratio between the GaAs- and the InP-SBD is rather as expected, not only for the small-signal regime when it is determined by the cut-off frequencies ratio (the latter is higher for GaAs [6]) but also for the large-signal regime when it is determined by the potential barrier heights ratio (which is also higher for GaAs). It is more difficult to explain a peak character of the spectral dependence of the sensitivity. The first peak could be explained by a growth of generation efficiency of nonequilibrium carriers when the radiation quantum energy approaches the semiconductor band-gap width and a subsequent growth of recombination efficiency caused by light absorption near the surface where recombination is more effective. The second peak around 80 μm might be a result

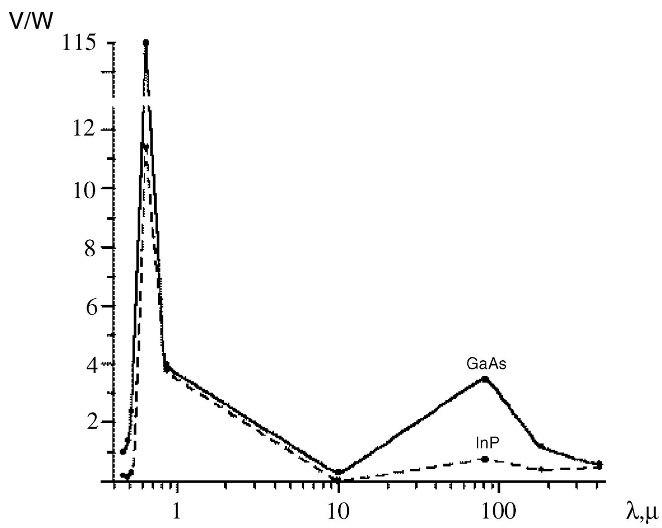

FIGURE 2 Spectral dependence of volt–watt sensitivity of GaAs-SBD and InP-SBD

of an interplay between different factors, such as nonhomogeneity of the spectral power density of radiation, dependence of the radiation coupling onto SBD on wavelength and perhaps others. The Fig. 2 plot does not include the results for the InGaAs-SBD since these diodes were investigated only in the range of 0.8 μm. At this wavelength a detector performance of the InGaAs-SBD was comparable to that of the InP diodes and significantly worse than that of GaAs.

For all diode types we detected video signals at the negative (reverse) bias which were not observed in the mid-IR and SMM ranges. This implies that in the near IR SBD work as photodetectors. The video-signal amplitudes in this case were 700 mV, 300 mV and 250 mV for the GaAs-, InP- and InGaAs-SBD, respectively (at the optimal bias current of $-20\,\mu$A and the Ti : sapphire laser power of 50 mW), which are by an order of magnitude higher than those at the direct bias [2].

The investigations of SBD in a mixer–multiplier mode, according to (1), were performed under the following conditions: the Ti : sapphire laser power $P_{\mathrm{Ti:S}} = 52$ mW, the GDO power $P_{\mathrm{g}} = 10$ mW and the GDO frequencies $f_{\mathrm{g}} = 38$, 76 and 140 GHz. The experimental results on the laser and the GDO frequencies mixing are presented in Fig. 3. As can be seen, in this wavelength range the InP-SBD turned out to be the most effective frequency converters. With these diodes we were able to obtain the beat signals between the Ti : sapphire laser modes with a difference up to 280 GHz (the 2nd harmonic of the GDO frequency of 140 GHz was used for heterodyning). Besides, with the InP diodes the beats using the 2nd harmonic of 76 GHz (S/N = 10 dB) and the 3rd harmonic of 38 GHz (S/N = 10 dB) have been obtained. With the GaAs- and InGaAs-SBD we could only get the signals at the difference frequency of 76 GHz (the 1st harmonic of the GDO) with S/N = 10 dB for the GaAs diodes and S/N = 5 dB for the InGaAs diodes. The beat-signal amplitude was limited mainly due to a deficit of the GDO and the laser power, since when the power was increased S/N grew as well. A necessity to use rather high laser power is determined by relatively low (less than 1 μW) power in each spectral component of a femtosecond laser. In accordance with the results of [1, 8], by increasing the laser and MM power one can also increase the mixing order.

The beat signals at the negative SBD bias were detected only with the InP diodes. S/N for these beats was reduced because of a higher noise. At the negative bias only the low-frequency beat signals between the Ti : sapphire laser modes were obtained; no beats between the laser frequencies and the GDO harmonics were found. This result is similar to the one reported in [9] for the GaAs-SBD. In [10] the authors also observed beat signals under the reverse bias for W–Ni point-contact metal–insulator–metal (MIM) diodes. In their case S/N did not depend on the bias sign and was mainly determined by contact parameters such as a sharper tungsten wire and a lighter contact pressure, resulting in a smaller capacitance of the diode and an improvement of its performance at the laser wavelengths up to 510 nm.

To study the mechanism responsible for observed effects in SBD it is interesting to determine a role of polarization and orientation effects characterized by the angles α and β (Fig. 1). Figure 4 represents a dependence of an amplitude of the beat signal between the Ti : sapphire laser modes on the angle α between the laser polarization plane and the beam incidence plane – a polarization characteristic of the diode antenna. This characteristic does not depend on the antenna material and SBD type but there is a dependence on the antenna diameter (or a ratio of the diameter to the radiation wavelength). With the increasing antenna diameter the polarization characteristic becomes less pronounced, for the amplitudes of the currents induced on the antenna at $\alpha = 0°$ and $\alpha = 90°$ level off. Qualitatively this result is expected: the closer an antenna length and width are to each other and the shorter a radiation wavelength, the lower a polarization sensitivity should be. The polarization effects and antenna properties were extensively studied for MIM diodes in different spectral ranges from MM to the infrared [11–14]. It was found that at frequencies below 10 THz the antenna acted like a long-wire antenna [11] while at higher frequencies it behaved like one-

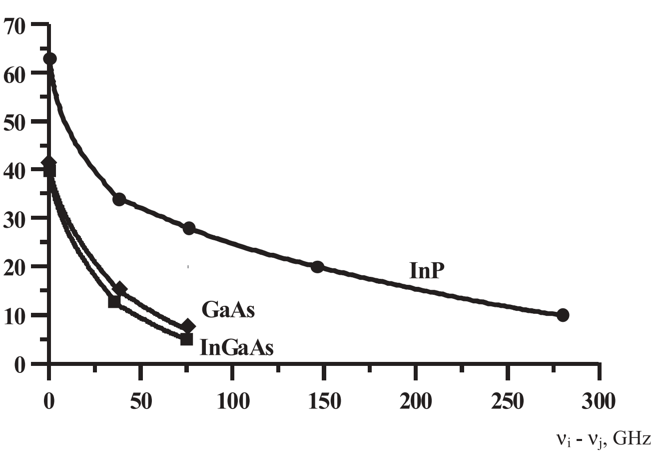

FIGURE 3 Signal-to-noise as a function of frequency difference between modes of Ti : sapphire laser for InP-, GaAs- and InGaAs-SBD

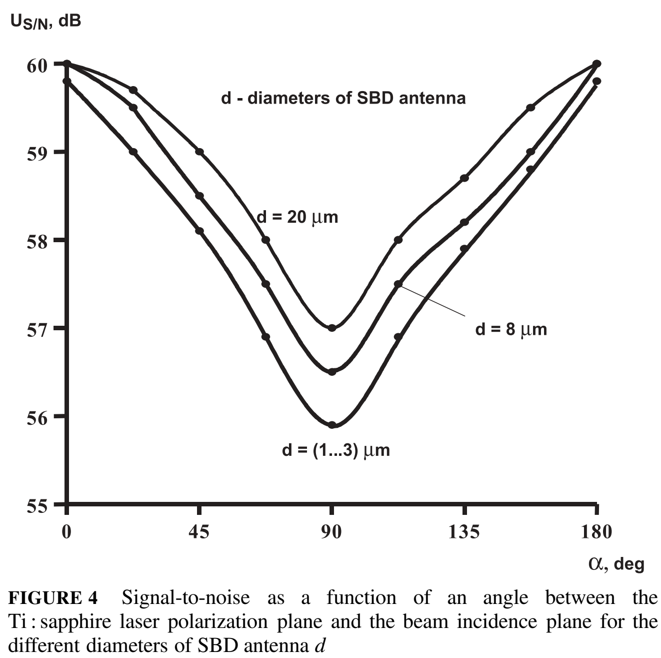

FIGURE 4 Signal-to-noise as a function of an angle between the Ti : sapphire laser polarization plane and the beam incidence plane for the different diameters of SBD antenna d

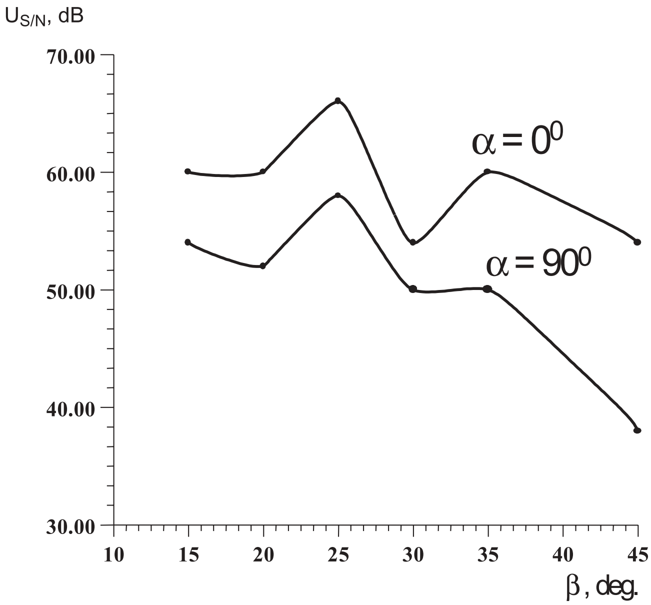

FIGURE 5 Signal-to-noise as a function of an angle between the diode antenna and the Ti : sapphire laser beam axes

half of a biconical antenna [12]. Although the mechanism of an influence of a laser polarization on the beats' amplitude should not depend on the specific diode junction, this effect was not widely explored for SBD. It was mentioned in [9], but there the authors changed the mutual polarization of lasers. In our experiment the mutual polarization of the Ti : sapphire laser modes remains the same; we changed the angle between the laser polarization plane and the beam incidence plane.

It was also experimentally shown that there is a dependence of an amplitude of the beat signal between the Ti : sapphire laser modes on the angle β between the diode antenna and the laser beam axes (Fig. 5). This dependence can be interpreted as the antenna directivity. The optimal angle is $\beta_{opt} \approx 25°$ and it is equal for $\alpha = 0°$ and $\alpha = 90°$. Unfortunately because of a poor angular resolution of the rotation stage used the graph of Fig. 5 presents only a qualitative dependence.

The obtained results witness in favor of a 'wave' character (as for long-wavelength radiation) interaction of laser radiation with SBD in the near IR. Although the antenna directivity was found and studied earlier for MIM diodes at MM to infrared wavelengths [11, 13, 14] and for SBD in the MM [15] and SMM ranges [16], it is demonstrated for SBD in the near IR for the first time to our knowledge.

3 Discussion

Experimental investigations of the detector, mixing and multiplying properties of various Schottky barrier diodes (SBD) in a wide wavelength range, from the submillimeter (SMM) to the near-IR range, were performed. They have revealed a very important feature of SBD – the ability to operate as detectors and frequency converters in all the investigated ranges. Only MIM diodes also possess such a broadband spectral sensitivity and high response speed [8, 10, 12, 13, 17] but they concede to SBD in mechanical stability and reproducibility of contact parameters, which seriously limit their practical use.

In contrast to MIM diodes where beat signals were observed under the negative diode bias currents (reverse bias) in the MM, SMM, IR and visible ranges [10], for reverse-biased SBD the appearance of beats was observed only in the near-IR range and was absent in the mid IR and SMM. However, as follows from experimental data, in this case the conversion efficiency (the signal-to-noise ratio and the mixing order) is much lower than in the conventional operation mode, at the positive (direct) SBD bias. All this indicates that here the mechanism of interaction of laser radiation with SBD is the same as at longer wavelengths. That is, the conversion is associated with the nonlinear properties of SBD. An additional argument in favor of this conclusion is that the influence of radiation polarization on the signal-conversion efficiency is, on the whole, similar for the long-wave and ultra-short-wave radiation.

An evident contradiction of this conclusion is that the SBD conversion efficiency is determined by its cut-off frequency. From this point of view, the best results should be expected from the GaAs-SBD, and not from the InP diodes, because the main parameter of the material that determines the cut-off frequency of SBD (all other conditions being equal), the carrier mobility, is higher for GaAs than for InP. This is in agreement (with some reservations) with the relation for the sensitivity of these diodes in a detector mode, but contradicts the results for a mixing–multiplying mode. In the latter case (in accordance with our data [2, 4] this is so also for the mid-IR region), the efficiency of the InP diodes is higher. At the same time, in the SMM range the higher conversion efficiency corresponds to the higher cut-off frequency. It is still not easy to understand this 'contradictory' behavior of the InP-SBD, and an explanation proposed below will require further clarification.

First of all, it should be noted that the lower height of the InP-SBD barrier cannot play a significant role in the explanation of peculiarities of its behavior, because the behavior of the InGaAs-SBD at the same low barrier height is 'usual'. Their efficiency both in detector and mixing–multiplying modes is lower than that of the GaAs-SBD, in accordance with the relation between their cut-off frequencies.

In a detector mode, the different sensitivity dependence for the GaAs- and InP-SBD on the bias current is evident [2]: for the GaAs diodes the optimal current is clearly defined and rather small (0.2–0.5 mA), and for the InP-SBD the sensitivity increases rather monotonically with the current (see Fig. 6 in [2]). For the InGaAs-SBD, the results can be considered 'intermediate'. One can conclude that barrier nonlinearity plays the main role for the GaAs-SBD sensitivity. At large biases, when the voltage begins to fall considerably at series resistance, the conversion efficiency decreases. For the InP-SBD, the bulk influence is more pronounced. This makes it possible to assume that bulk nonlinearity of indium phosphide can play a significant role in signal conversion. In the case of GaAs, the existence of this nonlinearity, confirmed by the presence of the Gunn effect, is well known. However, nonlinear properties of InP are more pronounced [18]. At the same time, in a detector regime, in which the constant component (video signal) is determined by the second Volt-Ampere characteristic (VAC) derivative, the effect of bulk nonlinearity is probably not so great, and the InP-SBD sensitivity remains lower, although it approaches the GaAs-SBD sensitivity as the bias increases.

It seems that the situation changes considerably in a mixing–multiplying mode. The results for the mid-IR range (a frequency of ~ 30 THz [2, 4]) are especially demonstrative. Beginning with the 4th mixing order, for the InP-SBD there are two peaks in the plot for the signal-to-noise ratio versus the bias current. This can be due to the influence of barrier and bulk nonlinearities. It is not inconceivable that at higher (7th and 8th) mixing orders both maxima of this plot are associated with the influence of bulk nonlinearity. One can also mention other results, which can be interpreted in favor of this influence. First, this is a relatively weak decrease in the signal-to-noise ratio with increase in the mixing order (Fig. 3, [4]), which is not typical for barrier nonlinearity. Second, this is the behavior of the signal-to-noise ratio at higher GDO power (Fig. 5, [4]). In the latter case, one can observe higher values of the signal-to-noise ratio for higher mixing orders. This can be due to a rather complex character of bulk nonlinearity, although a role of other factors cannot be excluded.

Unfortunately, at the present time it is hard to say something about the specific mechanism of signal conversion at bulk nonlinearity. To the above, one can only add that other properties of indium phosphide, such as lower (than in GaAs) values of time constants, which characterize the energy increase and relaxation of charge carriers in the electric field, also contribute to higher efficiency of the 'bulk' conversion in the InP-SBD. As we know [18], this indicates that nonlinearity is realized at higher frequencies. And, finally, let us dwell on lower nonequilibrium (heating) noise.

Particular attention should be given to the noise that determines the signal-to-noise ratio to the same extent as the signal conversion efficiency. It is well known that the SBD noise temperature T_{D}, which takes into account the barrier noise with the resistance R_j and the thermal noise of the series resistance r_{s}, can be represented in the following form [19, 20]:

$$T_{\mathrm{D}} = T_{\mathrm{B}} R_j/(R_j + r_{\mathrm{s}}) + T_r r_{\mathrm{s}}/(R_j + r_{\mathrm{s}}), \tag{2}$$

where T_{B} is the noise temperature of the barrier and T_r is the nonequilibrium noise temperature of the series resistance caused by the heating of the electron gas. A peculiarity of SBD under consideration is the fact that due to a small diameter of contacts (and, hence, high current densities) and a relatively low frequency of beats, the noise temperature of the barrier T_{B} is determined not only by the shot noise but also by the flicker noise [21, 22]:

$$T_{\mathrm{B}} \cong C_0 n j/4qf + nT/2. \tag{3}$$

Here C_0 is a constant depending weakly on the current, area, frequency and temperature, n is the ideality index of the diode's VAC, j is the current density, q is the electron charge and T is the temperature (SBD operation at direct bias is considered). In accordance with well-known data [23], in the planar GaAs-SBD the local current density can increase considerably due to the presence of zones with a smaller barrier height at the periphery of the contacts. This leads to an abrupt increase of the $1/f$ noise. Similar results for the InP-SBD are not known to us.

Investigations of the GaAs-SBD at rather high bias currents (> 1 mA) have shown that a considerable (and sometimes even decisive) contribution to the diode noise can be made by the noise temperature T_r. In accordance with [20],

$$T_r = T[1 + (\alpha I)^{\beta}], \tag{4}$$

where $\alpha = 0.03$–$0.037\ \mathrm{mA}^{-1}$ and $\beta = 2.1$–2.6. One should keep in mind that the amplitudes of the current caused by the joint action on the diode of the GDO power and the bias current can be rather large, which leads to a considerable heating of the electron gas. Such phenomena in the GaAs-SBD have been studied well [20]. As for the InP-SBD, no investigations of such kind are known to the authors. Theoretical estimates, however, show [24] that the expected heating noise in indium phosphide, at least at the fields of < 10 kW/cm, is much lower than in GaAs. Thus, it is reasonable to suppose that the high efficiency of the InP-SBD as a signal converter is a consequence of a stronger influence of bulk nonlinearity and, at the same time, of low noise. Besides, both effects are due to the fundamental properties of indium phosphide itself.

On the other hand, it remains unclear why the advantages of the InP-SBD in a mixing–multiplying mode manifest themselves beginning with the mid-IR region, and there are no advantages in the SMM range and at longer wavelengths [2, 4]. The nonmonotonic character of the sensitivity dependence in a detector mode on the wavelength needs an explanation (Fig. 2). More extensive investigations of the InP-SBD with a wider variation of diode parameters, regimes and conditions of measurements, especially in those frequency ranges where the contradictions mentioned exist, will probably be necessary to answer these questions.

4 Conclusion

In this paper, detector, mixing and multiplying properties of small-area Schottky diodes with a honeycomb structure of contacts, made from InP, GaAs and InGaAs in the near-IR spectral region were investigated. An attempt to generalize the results taking into account the data obtained earlier for longer wavelengths has been made.

In agreement with the well-known results it has been shown that SBD have a unique broadband spectral sensitivity from the millimeter wavelength range to the visible. Only point-contact metal–insulator-metal diodes also have comparable bandwidth and response speed but they are lacking mechanical stability and reproducibility of contact parameters and are limited in practical use.

The character of the signal conversion with SBD and the manifestation of polarization effects have made it possible to conclude that the nature of the conversion is the same for all the ranges investigated. It is supposed to be mainly associated with the nonlinear properties of SBD, in spite of relatively low (in comparison to the frequencies of the near-IR range) values of SBD cut-off frequencies.

In contrast to MIM diodes where beat signals were observed under the reverse diode bias in the ranges from millimeter to visible, for reverse-biased SBD the beats emerged only in the near IR. At SMM and mid-IR wavelengths these signals were not detected.

An unexpected result, which is hard to explain, is that at the frequencies of ≥ 30 THz the InP-SBD have a higher efficiency in a mixing–multiplying mode than the GaAs-SBD despite a lower cut-off frequency. This is reflected in the fact that they make it possible to detect a greater difference in laser frequencies and realize frequency mixing of a higher order. At the same time, in a detector mode the InP-SBD, as a rule, are much inferior to the GaAs-SBD.

The bulk properties of indium phosphide are used to explain the following features of the InP-SBD behavior: higher nonlinearity than in GaAs, which manifests itself in rather strong electric fields (that is, at rather large bias) and lower heating (nonequilibrium) noise. This hypothesis does not explain all aspects of the behavior of the InP-SBD. Therefore, additional investigations of the InP-SBD properties with a wider variation range of diode regimes and measurement conditions are required.

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