NUMERICAL MODELING OF DETECTION IN CONTACTS OF BISMUTH-ANTIMONY ALLOY WITH DIFFERENT MATERIALS: INFLUENCE OF CONTACT AREA AND MATERIAL FACTOR

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Abstract

Diode detectors (DDs) are widely used in electronic information and communication systems. In this paper, the numerical modeling of the electrical potential distribution and current passing in contacts of a normal metal or a superconductor with a bismuth-antimony (Bi–Sb) semiconductor alloy is conducted. The possibilities of designing DDs based on these contacts to operate at the liquid helium temperature (*T*) of 4.2 K are explored. The dependences of current responsivity (CR), voltage responsivity (VR), and noise equivalent power (NEP) on the signal frequency (*f*) are analyzed. The role of the contact area is discussed. The contacts of Bi–Sb with different materials are analyzed. The obtained results are compared to the literature data. Both DDs operating at the temperature of liquid nitrogen (*T* = 77.4 K) and liquid helium are considered. Comparison with existent literature data shows that the proposed DDs can be 10–100 times better. The physical reasons for these advantages are discussed. It is shown that the unique properties of Bi–Sb alloys, particularly of a $Bi_{0.88}Sb_{0.12}$ alloy, make these alloys promising materials for cryoelectronics.

1. Introduction

Diode detectors (DDs) play an important role in radio technique and electronics. The use of high frequencies (above 1 GHz) has stimulated a thorough study of Schottky-barrier diodes. These diodes are based on quick-acting metal–semiconductor contacts [1].

A further improvement of the parameters of diodes was achieved due to a decrease in the operating temperature. This direction is referred to as cryoelectronics [2]; it provides increasing the nonlinearity of the current-voltage dependences and current responsivity (CR). The thermal noise power decreases too. For example, DDs based on Pb-pGaAs ontacts have been developed [3, 4]. At the signal frequency of $f = 9$ GHz and $T = 4.2$ K, these diodes had CR ≈ 500 A/W and a noise equivalent power (NEP) of 5×10^{-15} W/$\sqrt{Hz}$.

In addition, deep cooling allows using the materials with a narrow energy gap and a high electron mobility, such as solid solutions Bi–Sb [2, 5].

After the discovery of high-temperature superconductors (HTSCs), the possibilities of using HTSCs in cryoelectronics were studied. At the liquid nitrogen temperature of $T = 77$ K and a signal frequency of $f = 37.5$ GHz, the respective structures exhibited a voltage responsivity (VR) of 3000 V/W [6]. Further studies [7] allowed creating structures with VR = 5000 V/W and

NEP = 2×10^{-12} W/$\sqrt{Hz}$ at a signal frequency of f = 31 GHz and a temperature of T = 77 K. According to our publication [8], the DDs based on HTSC–InSb contacts can have CR ≈ 40 A/W, VR ≈ 10^6 V/W, and NEP ≈ 8×10^{-15} W/$\sqrt{Hz}$ at T = 77.4 K and f = 10 GHz. At the same temperature and f = 30 GHz, these DDs can have CR ≈ 15 A/W, VR ≈ 3.5×10^5 V/W, and NEP ≈ 2×10^{-14} W/$\sqrt{Hz}$.

On the other hand, the semiconductor in HTSC–semiconductor contacts often undergoes oxidation because oxygen is an integral part of a HTSC. In addition, cooling to the liquid nitrogen temperature of 77.4 K may be insufficient to obtain good DD parameters. In this situation, taking into account the rapid development of cryogenics, the study of DDs based on conventional superconductor–semiconductor contacts seems to be an urgent problem. Usually, these DDs operate at liquid helium temperatures (T ≤ 4.2 K) [9, 10]. In this study, DDs based on the contacts of a superconductor (or a normal metal) with a Bi–Sb semiconductor solid solution are discussed.

2. Results and discussion

Contacts of semiconductor solid solution $Bi_{0.88}Sb_{0.12}$ with a normal metal or a superconductor were considered. The normal metal may be aluminum at $T \geq 1.2$ K and silver or gold at lower temperatures. Niobium or niobium nitride (NbN) may be chosen as superconductors at liquid helium temperatures. Material properties were taken from [11–13]. Results of calculations are shown in Figs. 1–6. In all the figures, a logarithmic scale for X-axes is used. An exponential form is often used for numbers of axes.

Figures 1–3 show the role of the contact area (for contacts with a normal metal). According to Figs. 1–3, the CR and VR decrease and NEP increases at frequencies higher than 3 GHz. At these frequencies, the negative role of the barrier capacity is revealed: it begins to shunt the nonlinear contact resistance. On the other hand, at high frequencies, the contact capacity resistance becomes comparable to ohmic spreading resistance. The current redistribution occurs; it leads to reduction of the rectified current and worsening of the DD parameters.

Round flat contacts with a contact area of 100, 10, and 1 μ^2 were studied. Taking into account the small surface area, these contacts may be considered as point contacts [1]. In this case, the barrier capacity is proportional to S, where S is the contact area, and the ohmic spreading resistance is proportional to $S^{-1/2}$ [1]. In this situation, where the contact area decreases, the capacity resistance increases faster than the ohmic spreading resistance. Therefore, the redistribution of the applied variable voltage occurs, the contact voltage increases, and the DD parameters become better (see curves 1–3 in Fig. 1). If the contact area decreases, the contact differential resistance and the VR increase. On the other hand, the noise current and the NEP decrease (see Figs. 2, 3).

The replacement of the metal by a superconductor leads to a significant improvement of the DD parameters (see Figs. 4–6). In contacts to superconductors, due to superconductor tunneling peculiarities [2], the current-voltage dependence becomes more nonlinear and the DD parameters are especially improved (compare curves *1* and *2* in Figs. 4–6). This effect increases with increasing superconductor energy gap (see curves *2* and *3* in Figs. 4–6). This fact points out the necessity to select superconductors with a wide energy gap (for example, NbN).

For comparison, our results [14] for HTSC-semiconductor contacts are shown in Figs. 7–9.

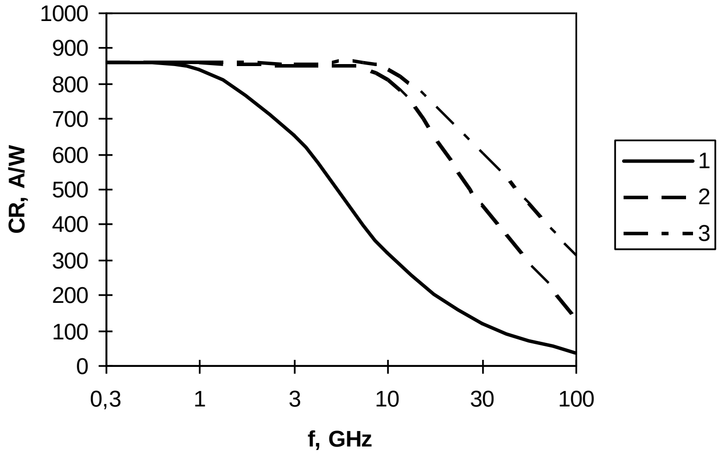

Fig. 1. Calculated dependence of the CR on the signal frequency in the contacts of a normal metal with $Bi_{0.88}Sb_{0.12}$. Inscriptions *1, 2,* and *3* correspond to the contact area of 100, 10 and 1 μ^2. T = 4.2 K.

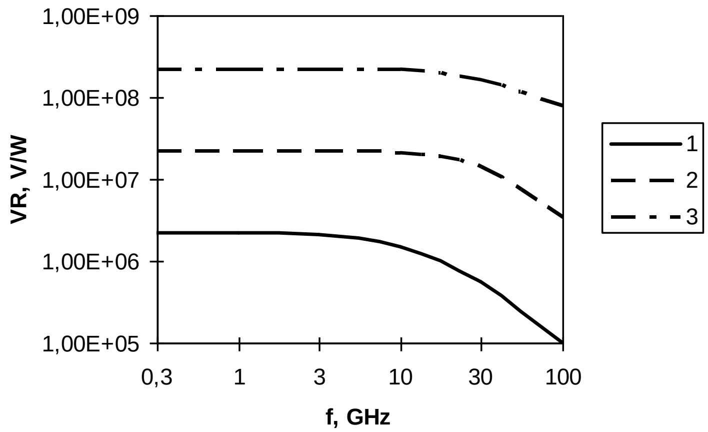

Fig. 2. Calculated dependence of the VR on the signal frequency. The inscriptions and other data are similar to those in Fig. 1. T = 4.2 K.

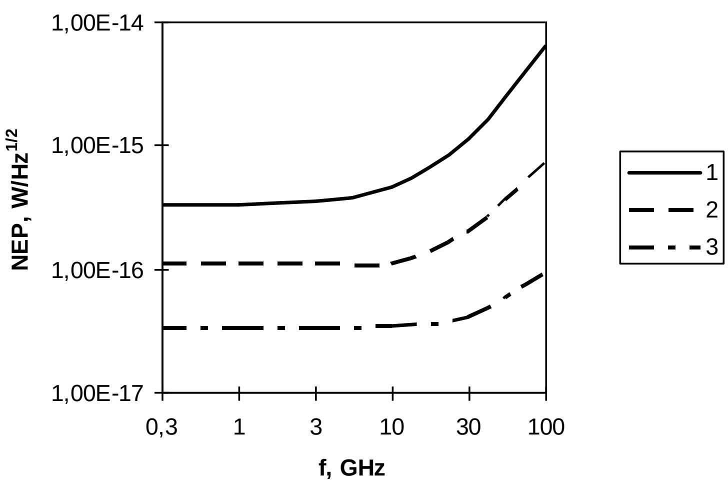

Fig. 3. Calculated dependence of the NEP on the signal frequency. The inscriptions and other data are similar to those in Fig. 1. T = 4.2 K

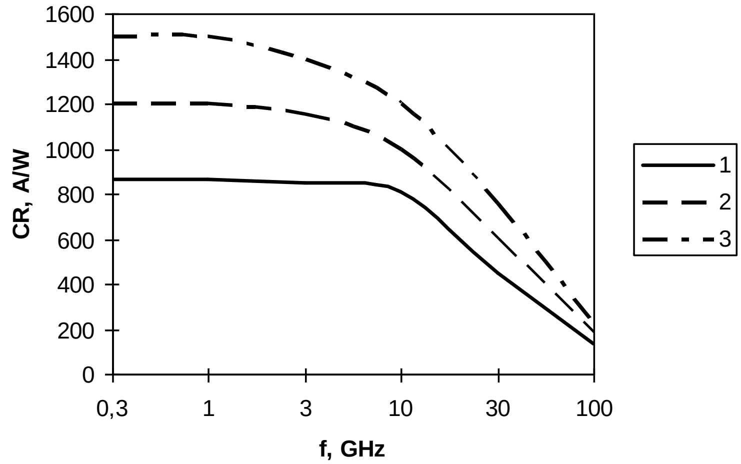

Fig. 4. Calculated dependence of the CR on the signal frequency in the contacts with $Bi_{0.88}Sb_{0.12}$. Inscriptions *1, 2,* and *3* correspond to the contacts with a normal metal, niobium, and niobium nitride, respectively. $T = 4.2$ K

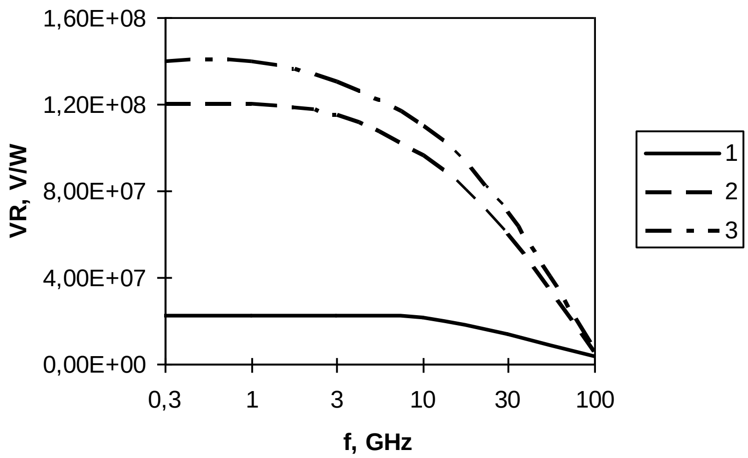

Fig. 5. Calculated dependence of the VR on the signal frequency in the contacts with $Bi_{0.88}Sb_{0.12}$. The inscriptions and other data are similar to those in Fig. 4. $T = 4.2$ K.

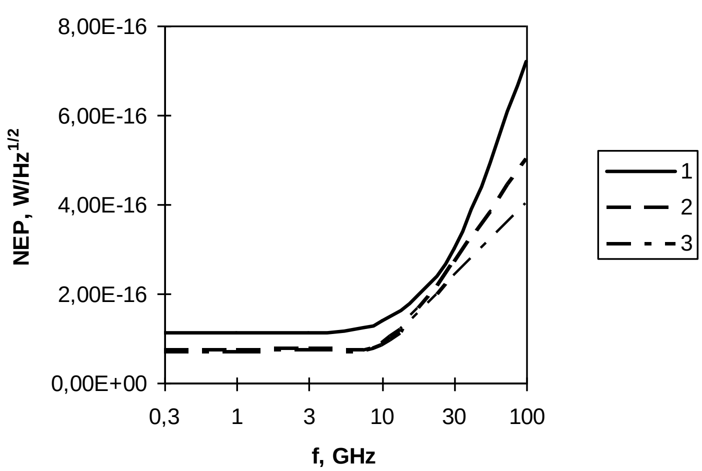

Fig. 6. Calculated dependence of the NEP on the signal frequency in the contacts with $Bi_{0.88}Sb_{0.12.}$ The inscriptions and other data are similar to those in Fig. 4. $T = 4.2$ K.

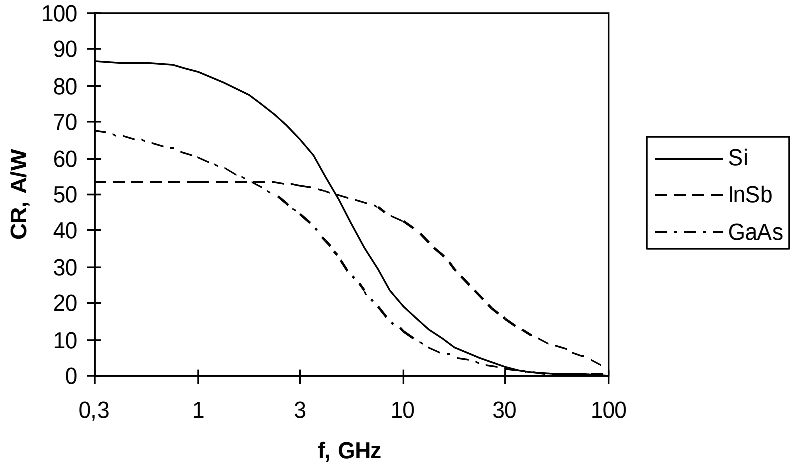

Fig. 7. Calculated dependence of the CR on the signal frequency for the HTSC–semiconductor contacts. The inscriptions show the semiconductor substance. T = 77.4 K

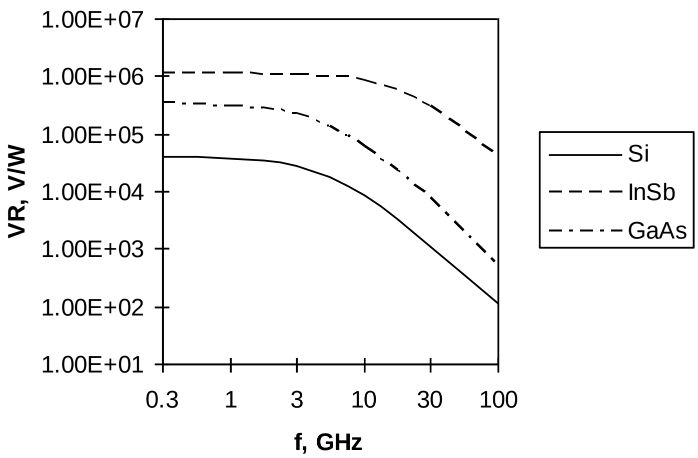

Fig. 8. Calculated dependence of the VR on the signal frequency for the HTSC–semiconductor contacts. The inscriptions and other data are similar to those in Fig. 5. T = 77.4 K.

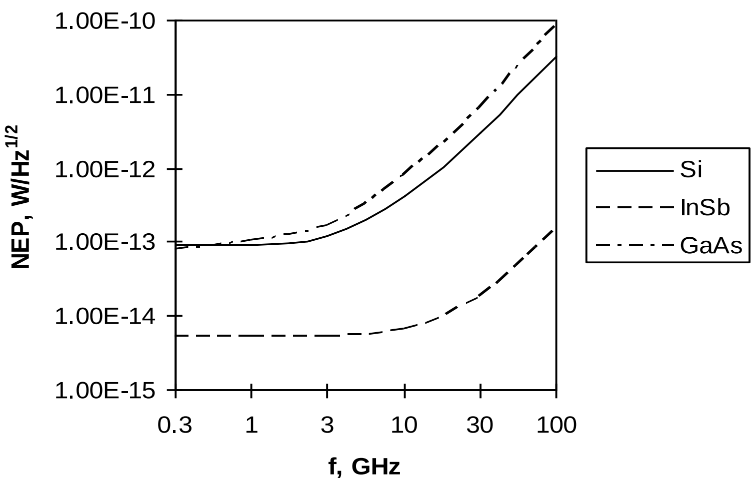

Fig. 9. Calculated dependence of the NEP on the signal frequency for the HTSC–semiconductor contacts. The inscriptions and other data are similar to those in Fig. 5. T = 77.4 K.

Taking into account the results of [3, 4, 6–8], we may conclude that contacts with a Bi–Sb allow considerably improve the DD parameters. They are much more effective than HTSC–superconductor contacts [6–8, 12]. They are also better than contacts with GaAs [3, 4] operating at the liquid helium temperature.

The main advantages of Bi–Sb are the following:

(i) Low barrier heights due to a narrow energy gap. This fact provides a considerable nonlinearity of CVD and a high CR.

(ii) High electron mobility, which reduces the ohmic resistance and improves the frequency behavior.

(iii) Low barrier capacity, due to low barrier heights and small effective masses of electrons, which also improves the frequency behavior.

These unique properties of Bi–Sb alloys, particularly of a $Bi_{0.88}Sb_{0.12}$ alloy, make these alloys to promising materials for cryoelectronics.

3. Conclusions

Comparison with the data of [3, 4, 8, 14] shows that the proposed DDs (based on contacts with Bi–Sb) can have a 2 times higher CR and a 50 times lower NEP than the existing DDs (at the same temperature and signal frequency). In addition, they can exhibit a very high VR. Their parameters can be a few orders of magnitude better than those of DDs operating at the liquid nitrogen temperature.

This fact suggests that the preparation of contacts with Bi–Sb is promising.

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