NUMERICAL MODELING OF DETECTION IN CONTACTS OF A BISMUTH-ANTIMONY ALLOY WITH DIFFERENT MATERIALS

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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 the contacts of a normal metal or a superconductor with a bismuth-antimony (Bi–Sb) semiconductor alloy are conducted. The possibilities to create DDs based on these contacts and working at the liquid helium temperature of 4.2 K or below are explored. The dependences of current responsivity (CR), voltage responsivity (VR), and noise equivalent power (NEP) on signal frequency (*f*) are analyzed. The role of the contact area is discussed. The obtained results are compared with literature data. DDs working at both the liquid nitrogen temperature (T = 77.4 K) and the liquid helium temperature are considered. The comparison with the available literature data shows that the proposed DDs can be 10÷100 times better. The physical reasons of these advantages are discussed. It is shown that unique properties of Bi-Sb alloys and especially of a $Bi_{0.88}Sb_{0.12}$ alloy make these alloys promising materials for cryoelectronics.

1. Introduction

The diode detectors (DDs) play an important role in radio engineering and electronics. The use of high frequencies (above 1 GHz) stimulated a careful study of Schottky-barrier diodes. These diodes use quick-acting metal-semiconductor contacts [1].

A further improvement of their parameters was achieved due to a decrease in the working temperature. This direction was termed cryoelectronics [2]; it gives the possibility to increase the nonlinearity of current-voltage dependences and current responsivity (CR). The thermal noise power decreases too. For example, DDs based on Pb–pGaAs contacts have been designed [3, 4]. At a 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/$\sqrt{Hz}$. At the same frequency and T = 1 K the parameters were as follows: CR ≈ 2500 A/W and NEP = 5.4×10-16 W/$\sqrt{Hz}$. In addition, deep cooling allows using materials with a small energy gap width and a high electron mobility, such as solid solutions Bi–Sb [2, 5].

After the discovery of high temperature superconductors (HTSCs), the possibilities to use HTSCs in cryoelectronics were studied too. At the liquid nitrogen temperature of T = 77 K and a signal frequency of f = 37.5 GHz, the corresponding structures revealed the voltage responsivity (VR) of 3000 V/W [6]. Further studies [7] made it possible to create 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], DDs based on HTSC-InSb contacts may have CR ≈ 40 A/W, VR ≈ 106 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 may have CR ≈ 15 A/W, VR ≈ 3.5×105 V/W, and NEP ≈ 2×10-14 W/$\sqrt{Hz}$.

On the other hand, the semiconductor often undergoes oxidation in HTSC-semiconductor contacts, because oxygen is an integral part of HTSCs. 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 traditional superconductor–semiconductor contacts seems to be an urgent problem. Usually, these DDs work at liquid helium temperatures (T ≤ 4.2 K) [9, 10]. In this study, DDs based on contacts between a superconductor (or a normal metal) and a Bi−Sb semiconductor solid solution are discussed.

2. Results and discussion

Contacts between a $Bi_{0.88}Sb_{0.12}$ semiconductor solid solution and 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. Materials 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 1−6 show that current and voltage responsivities decrease and NEP increases at frequencies above 3 GHz. At these frequencies, the negative role of the barrier capacity is revealed and it begins to shunt the nonlinear contact resistance. The current redistribution occurs; it leads to a reduction in the rectified current, and DD parameters become worse.

If a metal is replaced by a superconductor, the DD parameters are significantly improved. This is particularly true for the case in which the working temperature decreases from 4.2 to 1 K and the current passes due to field emission [2]. In contacts with normal metals, CVD nonlinearity and CR hardly depend on temperature [1, 2]. But in contacts with superconductors, owing to specific features of superconductor tunneling [2], the CVD nonlinearity increases and DD parameters are significantly improved (compare curves *1* and *2* in Figs. 1–6). This effect increases for a wider superconductor energy gap (see curves *2* and *3* in Figs. 16). This fact points out the necessity to select superconductors with a wide energy gap (e.g., NbN).

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

Taking into account the results of [3, 4, 6–8], we can conclude that contacts with Bi−Sb allow considerably improving DD parameters. They are much more effective than HTSC-superconductor contacts [6–8, 12]. In addition, they are better than contacts with GaAs [3, 4] that operate at the liquid helium temperature.

The main advantages of Bi−Sb are as follows:

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

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

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

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

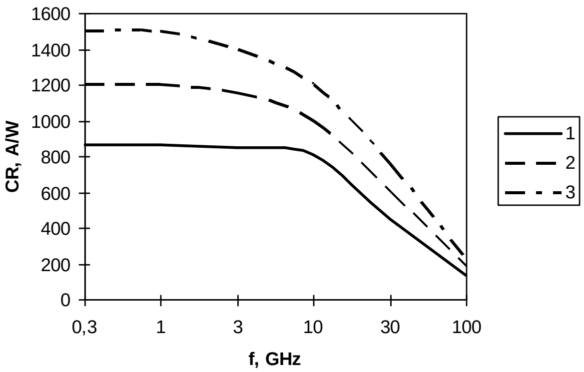

Fig. 1. Calculated dependence of CR on signal frequency. Legend inscriptions 1, 2, and 3 correspond to the contacts with a normal metal, niobium, and niobium nitride, respectively. $T = 4.2$ K.

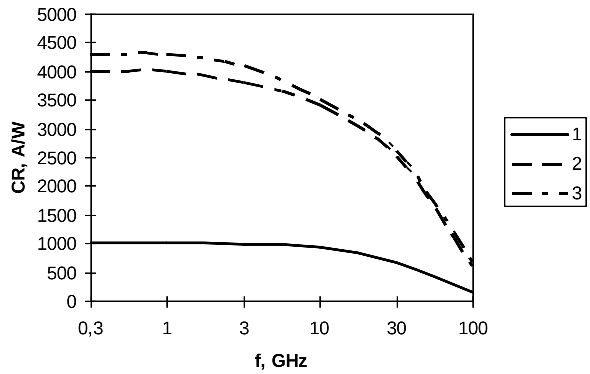

Fig. 2. Calculated dependence of CR on signal frequency. The legend inscriptions are similar to those in Fig. 1. $T = 1$ K.

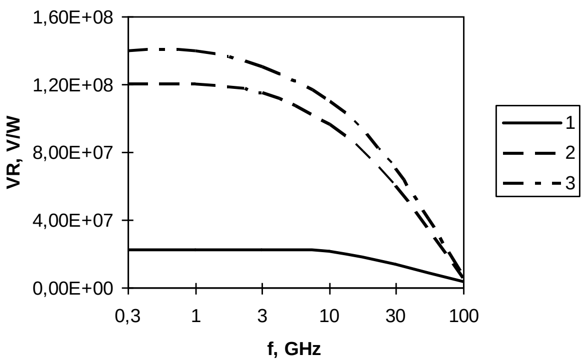

Fig. 3. Calculated dependence of VR on signal frequency. The legend inscriptions are similar to those in Fig. 1. $T = 4.2$ K.

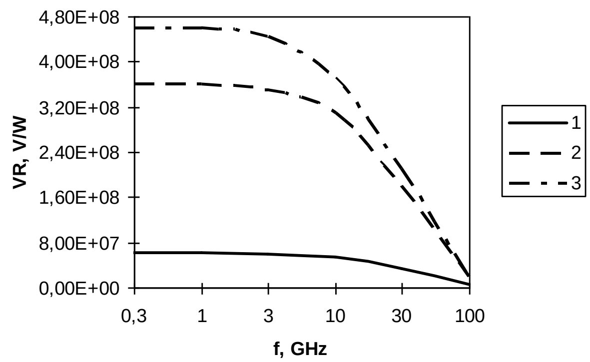

Fig. 4. Calculated dependence of VR on signal frequency. The legend inscriptions are similar to those in Fig. 1. $T = 1$ K.

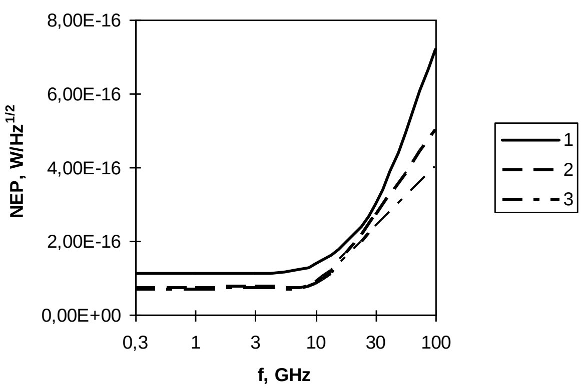

Fig. 5. Calculated dependence of NEP on signal frequency. The legend inscriptions are similar to those in Fig. 1. $T = 4.2$ K.

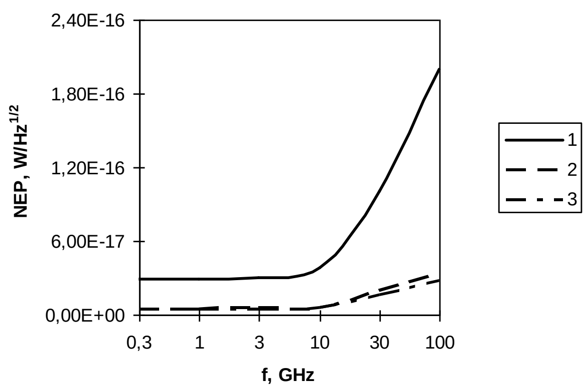

Fig. 6. Calculated dependence of NEP on signal frequency. The legend inscriptions are similar to those in Fig. 1. $T = 1$ K.

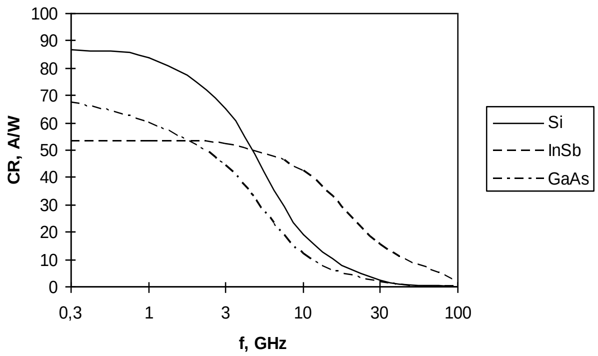

Fig. 7. Calculated dependence of CR on signal frequency for HTSC-semiconductor contacts. The legend inscriptions show the semiconductor substance. T = 77.4 K.

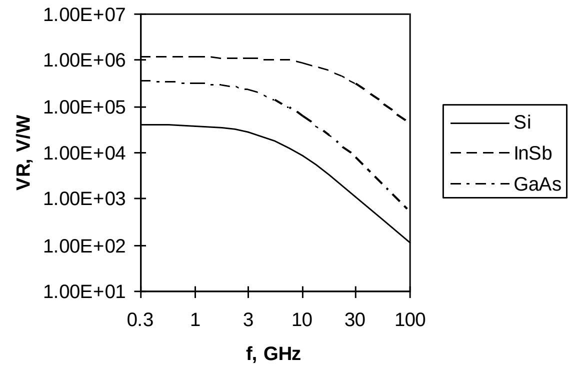

Fig. 8. Calculated dependence of VR on signal frequency for HTSC-semiconductor contacts. The legend inscriptions and other data are similar to those in Fig. 5. T = 77.4 K.

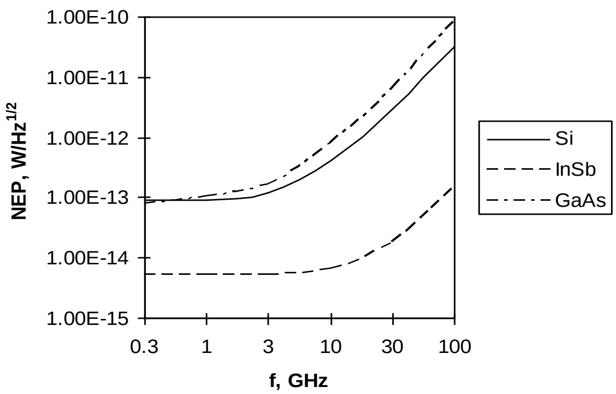

Fig. 9. Calculated dependence of NEP on signal frequency for HTSC-semiconductor contacts. The legend inscriptions and other data are similar to those in Fig. 5. T = 77.4 K.

3. Conclusion

The comparison with the data in [3, 4, 8, 14] shows that, if the surface states are in thermodynamic equilibrium with superconductor, the proposed DDs may have 2 times higher CR and 50 times lower NEP than in existing DDs (at the same temperature and signal frequency). In addition, they may have a very high VR. This fact suggests that contacts with Bi–Sb are promising.

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