

Detection in the contacts with bismuth-antimony alloy: influence of the free electrons concentration on the current responsivity

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Abstract - Diode detectors (DD) 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 niobium nitride (NbN) with semiconductor alloy bismuth-antimony (Bi-Sb) was made.

The contacts of Bi-Sb with different materials were studied. Also it was studied situation, when the surface states have no time to recharge with applied electric voltage (a "dynamic" regime). There were analyzed possibilities to create the diode detectors based on these contacts and working at liquid helium temperatures 4.2 K and 1 K. The dependences of the current responsivity (CR), the voltage responsivity (VR) and the noise equivalent power (NEP) on the signal frequency (f) were analyzed. The dependences of the current responsivity on the free electrons concentration was analyzed too. The obtained results were compared with literature data. Both DD working at temperature of liquid nitrogen (T = 77.4 K) and liquid helium were considered.

The comparison with existent literature data shows the proposed DD can be 10-100 times better. The physical reasons of these advantages were discussed. It is shown that unique properties of Bi-Sb alloys and especially of $\text{Bi}_{0.88}\text{Sb}_{0.12}$ alloy make these alloys to be the very perspective materials for cryoelectronics.

Index terms - detection, Schottky diodes, superconductivity.

I. INTRODUCTION

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

The further improvement of their parameters was achieved due to fall of the working temperature. This direction was named cryoelectronics [2], it allows to raise the nonlinearity of the current-voltage dependences and current responsivity. The thermal noise power decreases too. For example there were elaborated DD based on the contacts Pb-pGaAs [3, 4]. At the signal frequency $f = 9$ GHz and $T = 4.2$ K these diodes had $\text{CR} \approx 500$ A/W and noise equivalent power 5×10^{-15} W/ $\sqrt{\text{Hz}}$. At the same frequency and $T = 1$ K there parameters were: $\text{CR} \approx 2500$ A/W and noise equivalent power 5.4×10^{-16} W/ $\sqrt{\text{Hz}}$. Also the deep cooling allows using the materials with little energy gap width but high mobility of electrons, such as solid solutions Bi-Sb [2, 5].

After the discovery of the high temperature superconductors (HTSC) the possibilities to use HTSC in cryoelectronics were studied too. At the liquid nitrogen temperature $T = 77$ K and signal frequency $f = 37.5$ GHz the corresponding structures revealed the voltage responsivity 3000 V/W [6]. The further studies [7] allowed to create the structures with $\text{VR} = 5000$ V/W and noise equivalent power $\text{NEP} = 2 \times 10^{-12}$ W/ $\sqrt{\text{Hz}}$ at the signal frequency $f = 31$ GHz and temperature $T = 77$ K. According to our publication [8] the diode detectors

based on the contacts HTSC-InSb may have $\text{CR} \approx 40$ A/W, $\text{VR} \approx 10^6$ V/W and $\text{NEP} \approx 8 \times 10^{-15}$ W/ $\sqrt{\text{Hz}}$ at $T = 77.4$ K and $f = 10$ GHz. At the same temperature and $f = 30$ GHz these DD may have $\text{CR} \approx 15$ A/W, $\text{VR} \approx 3.5 \times 10^5$ V/W and $\text{NEP} \approx 2 \times 10^{-14}$ W/ $\sqrt{\text{Hz}}$.

On the other hand often there is an oxidation of semiconductor in HTSC-semiconductor contacts, because oxygen is an integral part of HTSC. In this situation, taking into account the rapid development of cryogenics, the study of DD based on the contacts traditional superconductor – semiconductor seems to be actual problem. Usually these DD work at liquid helium temperatures ($T \leq 4.2$ K). In this paper the numerical modeling of the electrical potential distribution and current passing in the contacts of niobium nitride (NbN) with semiconductor alloy bismuth-antimony (Bi-Sb) was made.

II. RESULTS AND DISCUSSION

The contacts of semiconductor solid solution $\text{Bi}_{0.88}\text{Sb}_{0.12}$ with normal metal or 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 [9-11]. Figure (fig.) 1 shows the calculated current responsivity dependence on the free electrons concentration (FEC) in $\text{Bi}_{0.88}\text{Sb}_{0.12}$.

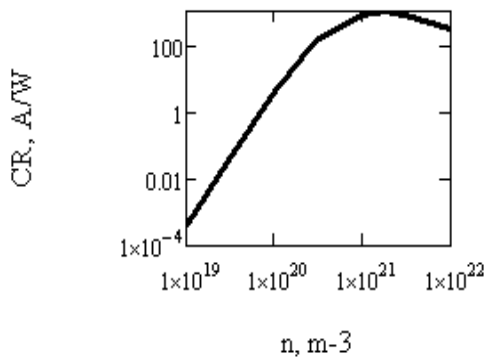


Fig. 1. The calculated current responsivity dependence on the on the free electrons concentration (FEC) in $\text{Bi}_{0.88}\text{Sb}_{0.12}$ at the signal frequency $f = 1$ GHz and $T = 4.2$ K.

At first the current responsivity increases with FEC rise because the ohmic volume resistance drops faster than the contact capacity resistance. This effect increases the signal voltage applied to contact and signal power absorbed in contact and transformed in rectified current.

Howe ever further FEC rise above 1021 m^{-3} leads to increasing of the barrier permeability. This fact reduces the nonlinearity of the current-voltage and current responsivity decreases too.

ther results of calculations are shown in figures (figs.) 2-5. In all figures the logarithmic scale for X-axes is used. An exponential form is often used for numbe rs of axes.

Figs. 2 - 5 show that current responsivity decreases and NEP increases at the frequencies more 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 reduction of the rectified current and DD parameters become worse.

If metal is replaced by superconductor the DD parameters are improved essentially. It is especially seen when working temperature falls from 4.2 K to 1 K and current passes due to field emission [2]. Then in contacts with normal metals CVD nonlinearity and current responsivity practically do not depend on temperature [1, 2]. But in contacts with superconductors due to superconductor tunneling peculiarities [2] CVD nonlinearity rises and DD parameters are improved especially (compare curves 1 and 2 in figs. 2-5). This effect increases when superconductor energy gap is more (see curves 2 and 3 in figs. 2-5). This fact points out the necessity to select superconductor with wide energy gap (for example NbN).

Taking into account results [3, 4, 6-8] we may co nclude that contacts with Bi-Sb allow improving considerably DD parameters. On one hand they are much more effective than contacts HTSC-superconductor [6-8]. On the other hand they are better than contacts with GaAs [3, 4].

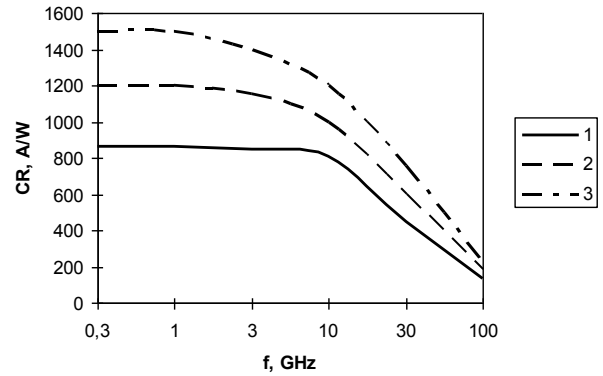


Fig. 2. The calculated current responsivity dependence on the signal frequency. The legend inscriptions 1, 2 and 3 correspond to the contacts with normal metal, niobium and niobium nitride accordingly. $T = 4.2$ K.

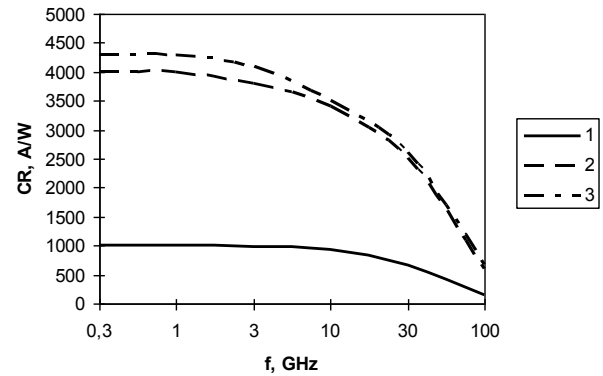


Fig. 3. The calculated current responsivity dependence on the signal frequency. The legend inscriptions are similar to those at fig. 2. $T = 1$ K.

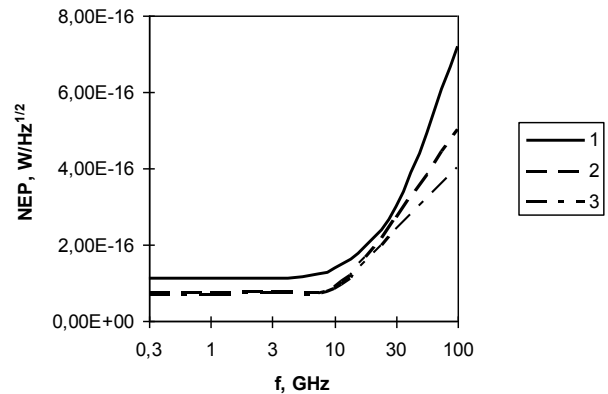


Fig. 4. The calculated noise equivalent power dependence on the signal frequency. The legend inscriptions are similar to those at fig. 2. $T = 4.2$ K.

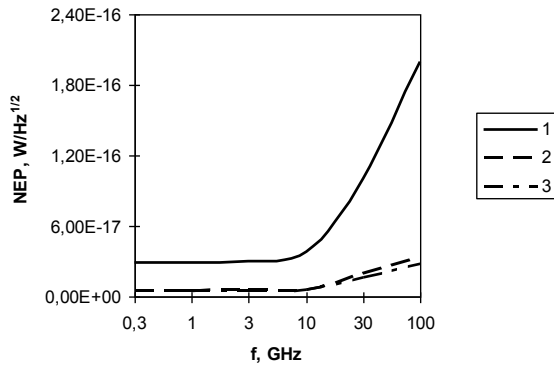


Fig. 5. The calculated noise equivalent power dependence on the signal frequency. The legend inscriptions are similar to those at fig. 2. $T = 1$ K.

Earlier we studied situation when the surface states had time to recharge with applied electric voltage (a “static” regime). In this article also an opposite situation is studied, when the surface states have no time to recharge with applied electric voltage (a “dynamic” regime). Materials properties were taken from [10, 11]. Results of calculations are shown in figures (figs.) 5-7. In all figures the logarithmic scale for X-axes is used. An exponential form is often used for numbers of axes.

The comparison with the “static” regime shows that also in dynamic regime DD based on Bi-Sb may have the very good parameters.

The reduction of the working temperature from 4.2 K to 1 K may sufficiently improve these parameters.

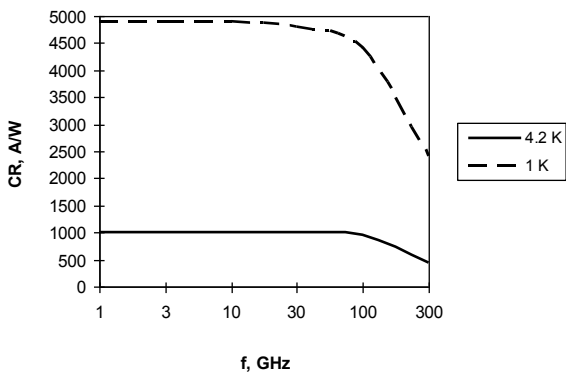


Fig. 6. The calculated current responsivity dependence on the signal frequency in the contacts with $\text{Bi}_{0.88}\text{Sb}_{0.12}$. The legend inscriptions show the working temperature.

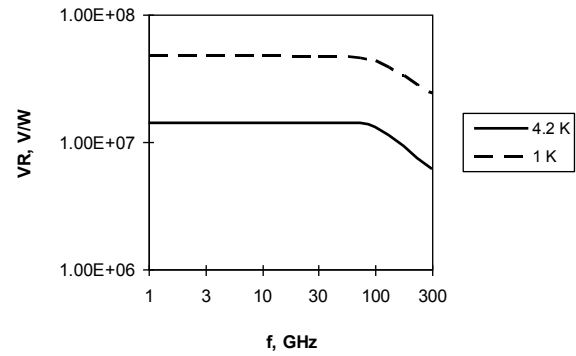


Fig. 7. The calculated voltage responsivity dependence on the signal frequency.

The legend inscriptions and other data are similar to those in fig. 6

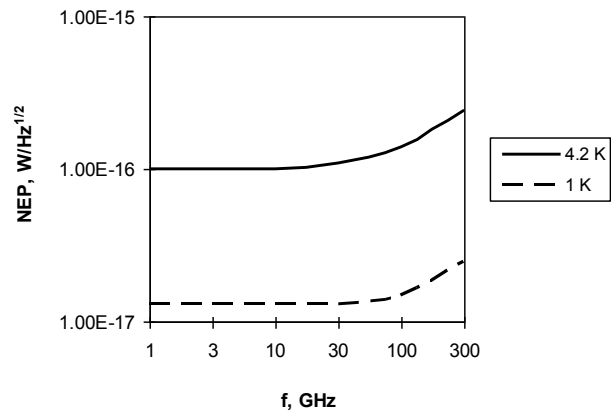


Fig. 8. The calculated noise equivalent power dependence on the signal frequency. The legend inscriptions and other data are similar to those in fig. 6.

The main advantages of Bi-Sb are next:

(i) Little barriers heights due to narrow energy gap. This fact provides a big CVD nonlinearity and big current responsivity.

(ii) High mobility of electrons, which reduces ohm resistance and improves frequencies properties.

(iii) Little barrier capacity, due to little barriers heights and small effective masses of electrons, which also improves frequencies properties.

These unique properties of Bi-Sb alloys and especially of $\text{Bi}_{0.88}\text{Sb}_{0.12}$ alloy make these alloys to be the very perspective materials for cryoelectronics.

For comparison our results [12] for contacts HTSC-semiconductor with contact area $100 \mu^2$ are presented in figs. 9,10.

Taking into account results [3, 4, 6-8] we may conclude that contacts with Bi-Sb allow improving considerably DD parameters. They are much more effective than contacts HTSC-superconductor [6-8]. Also they are better than contacts with GaAs [3, 4] working at liquid helium temperature.

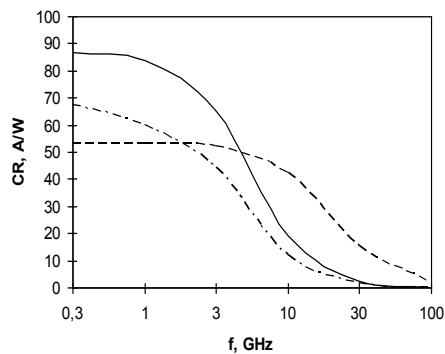


Fig. 9. The calculated current responsivity dependence on the signal frequency for contacts HTSC-semiconductor (the semiconductor substance is shown in legend inscriptions). $T = 77.4$ K.

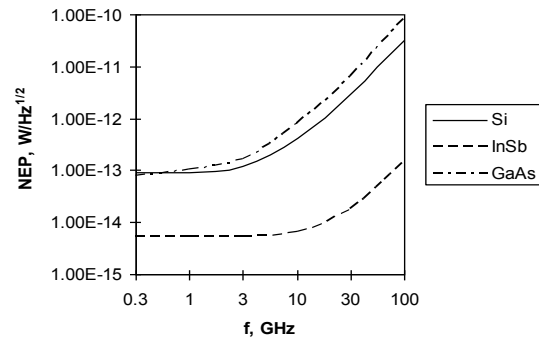


Fig. 10. The calculated noise equivalent power dependence on the signal frequency for contacts HTSC-semiconductor. The legend inscriptions and other data are similar to those in fig. 9. $T = 77.4$ K.

III. CONCLUSION

The comparison with [3, 4, 9] data shows that also in dynamic regime the proposed DD may have the current responsivity 2 times more and noise equivalent power 50 times less than the ones in existing DD (at the same temperature and signal frequency). Also they may have very high voltage responsivity.

The contact area reduction may sufficiently improve the frequencies properties, noise equivalent power and especially voltage responsivity.

This fact draws the conclusion the contacts with Bi-Sb are perspective to elaborate them.

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