

Detection in the Structures Based on a Semiconductor (Bi-Sb)/Superconductor (NbN) Contacts: Optimization for High Frequency Signal

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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 optimization for high frequency signal was realised, when the signal frequency is more 10 GHz. There were analyzed possibilities to create the diode detectors based on these contacts and working at temperatures (T) of liquid helium 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 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 Bi_{0.88}Sb_{0.12} alloy make these alloys to be the very perspective materials for cryoelectronics.

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 $CR \approx$

500 A/W and noise equivalent power 5×10^{-15} W/ \sqrt{Hz} . At the same frequency and $T = 1$ K there parameters were: $CR \approx 2500$ A/W and noise equivalent power 5.4×10^{-16} W/ \sqrt{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 $VR = 5000$ V/W and

noise equivalent power $NEP = 2 \times 10^{-12}$ W/ \sqrt{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 $CR \approx 40$ A/W, $VR \approx 10^6$ V/W and $NEP \approx 8 \times 10^{-15}$ W/ \sqrt{Hz} at $T = 77.4$ K and $f = 10$ GHz. At the same temperature and $f = 30$ GHz these DD may have $CR \approx 15$ A/W, $VR \approx 3.5 \times 10^5$ V/W and $NEP \approx 2 \times 10^{-14}$ W/ \sqrt{Hz} .

On the other hand often there is an oxidation of semiconductor in HTSC-semiconductor contacts, because oxygen is an integral part of HTSC. Also cooling to the liquid nitrogen temperature 77.4 K may be insufficient to obtain the good DD parameters. 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 with semiconductor alloy bismuth-antimony was made for situation when the surface states have a big density.

II. RESULTS AND DISCUSSION

The contacts of semiconductor solid solution Bi_{0.88}Sb_{0.12} with NbN were considered, because according to our results [9] these contacts seem to have the best parameters. The round flat contacts with contact area $1 \mu^2$ were studied. The optimization for high frequency signal was realised, when the signal frequency is more 10 GHz. Materials properties were taken from [9 - 11]. Results of calculations are shown in figures (figs.) 1-3. In all figures the logarithmic scale for X-axes is used. An exponential form is often used for numbers of axes.

Figs. 1 - 3 show that current and voltage responsivities decrease and NEP increases at the frequencies more 10 GHz. At these frequencies the negative role of the barrier capacity is revealed and it begins to shunt the nonlinear contact resistance. On the other hand at high frequencies the contact capacity resistance becomes compared with ohm spreading resistance. The current redistribution occurs, it leads to reduction of the rectified current and DD parameters become worse.

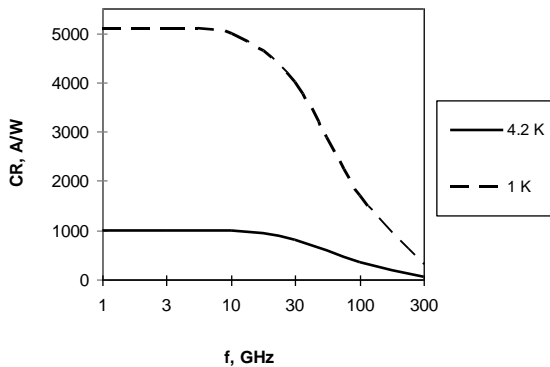


Fig. 1. The calculated current responsivity dependence on the signal frequency in the contacts with $\text{Bi}_{0.88}\text{Sb}_{0.12}$. The legend inscriptions show the working temperatures.

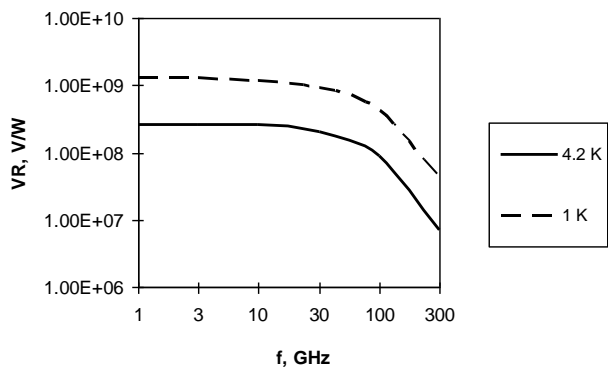


Fig. 2. The calculated voltage responsivity dependence on the signal frequency in the contacts with $\text{Bi}_{0.88}\text{Sb}_{0.12}$. The legend inscriptions show the working temperatures.

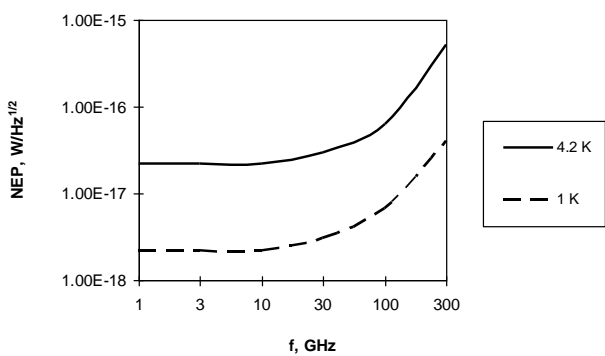


Fig. 3. The calculated noise equivalent power dependence on the signal frequency. The legend inscriptions show the working temperatures.

Also the reduction of the working temperature from 4.2 K to 1 K may sufficiently improve these parameters. On one hand nonlinearity of the current – voltage characteristic rises sufficiently, that leads to increase of the current responsivity, voltage responsivity and noise equivalent power [1 - 3]. On the other hand noise current falls and this effect provides with additional reduction of noise equivalent power [1 - 4].

The comparison with our data [10] shows that also in situation, when the surface states have a big density, DD based on Bi-Sb may have the very good parameters.

For comparison our results [14] for contacts HTSC-semiconductor are presented in figs. 4 - 6.

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, 12]. Also they are better than contacts with GaAs [3, 4] working at liquid helium temperature.

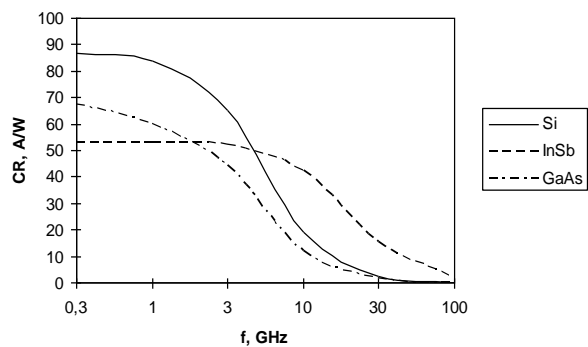


Fig. 4. The calculated current responsivity dependence on the signal frequency for contacts HTSC-semiconductor. The legend inscriptions show the semiconductor substance. $T = 77.4 \text{ K}$.

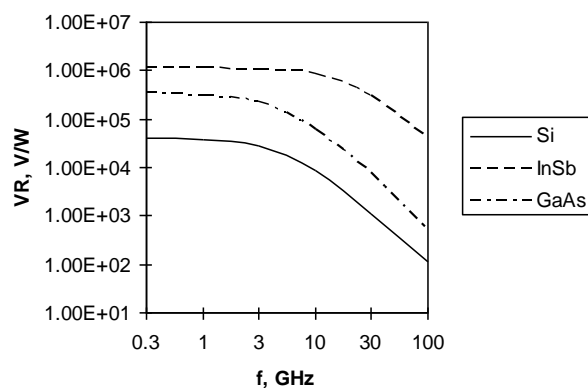


Fig. 5. The calculated voltage responsivity dependence on the signal frequency for contacts HTSC-semiconductor. The legend inscriptions and other data are similar to those in fig. 4. $T = 77.4 \text{ K}$.

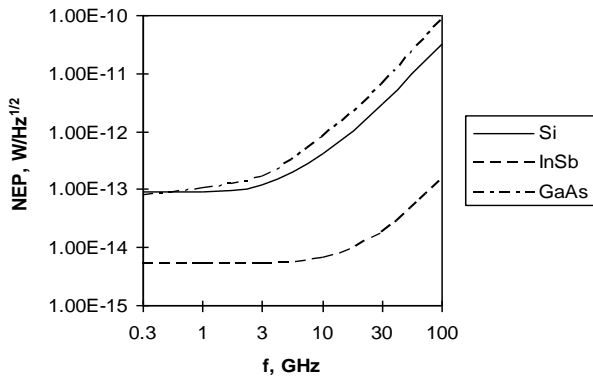


Fig. 6. The calculated noise equivalent power dependence on the signal frequency for contacts HTSC-semiconductor. The legend inscriptions and other data are similar to those in fig. 4. $T = 77.4$ K.

The main advantages of Bi-Sb are next:

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

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

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

III. CONCLUSIONS

The comparison with [3, 4, 8, 12] data shows that also in situation, when the surface states have a big density, the proposed DD may have the current responsivity 2 times more and noise equivalent power 100 times less than the ones in existing DD (at the same temperature and signal frequency).

On the other hand they may have the current responsivity 50 times more, voltage responsivity 300 times more and noise equivalent power 300 times less than the diodes working at the liquid nitrogen temperature.

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

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