HTSC – Si AND HTSC – InSb CONTACTS FOR DIODE DETECTORS: COMPARISON OF CHARACTERISTICS

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(Received 14 September 2006)

The numerical calculations of the electrical potential distribution and current passing in the contacts of the high temperature superconductor (HTSC) with semiconductors silicon (Si) and indium antimonite (InSb) were carried out. There were analyzed the possibilities to prepare the diode detectors (DD) based on these contacts and working at liquid nitrogen temperature 77.4K.

The comparison of structures based on Si and InSb was carried out. The obtained results were explained taking into account the physical properties of these semiconductors. Both advantages and disadvantages of these materials were discussed. The optimum application spheres were determined for Si and InSb accordingly.

The comparison of the obtained results with existent literature data shows that the proposed DD can be 10÷100 times better than the existing devices. Therefore, these DD are perspective for cryogenic electronics, and their preparation is a problem of today.

Introduction

At present, the perspectives of technical application of the high temperature superconductors (HTSC) are widely studied. The possibilities to prepare the diode detectors (DD) with Josephson HTSC junctions have been also investigated. At the liquid nitrogen temperature T=77 K and signal frequency f = 37.5 GHz the corresponding structures revealed the voltage responsivity VR=3000 V/W [1]. The further studies [2] allowed preparation of structures with VR=5000 V/W and noise equivalent power NEP = 2×10^{-12} W/Hz$^{1/2}$ at the signal frequency f=31 GHz and temperature T=77 K. We suppose that it is possible to prepare DD working at T=77.4 K being based on the HTSC-semiconductor contacts. These structures are the Schottky super diodes. HTSC is used instead of metal. According to [3] this substitution may sufficiently increase the nonlinearity of the current-voltage dependences (CVD) due to peculiarities of the electronic density of states in superconductor. These DD can detect the radio frequency signals and they can provide very high parameters due to this high nonlinearity. The band diagram of this structure is similar to the one in [3]. At present the contacts of HTSC with semiconducting SrTiO3 [4] and GaAs/AlAs superlattices [5] are already obtained. Taking into account the experimental problems, the numerical analysis seems to be an urgent task.

In order to solve this problem the calculation method was developed and the numerical analysis of the contacts of HTSC-semiconductor (Si or InSb) was made. The potential distribution, current-voltage dependences and DD parameters were calculated. The surface states at the boundary, the charges of electrons and holes in the narrow gap semiconductors, the superconductor tunneling peculiarities and other phenomena were taken into account. The flat contacts with a 100μ^2 area were considered, and estimated current density in InSb was more than 6 orders less than the critical one [6].

Results and discussion
1. The influence of the free electron concentrations in silicon

Earlier we have analyzed the dependences of contact properties on the free electron concentration (FEC) *n* in InSb for contacts with normal metal and HTSC [7, 8]. In this article the corresponding analysis for contacts HTSC – Si is presented. Fig. 1 shows the calculated current responsivity (CR) dependence on FEC in Si (at f=1, 10, 30 GHz). In this article, an exponential form is often used for numbers of axes. For example 3, 00E+19 signifies 3×10^{19} and 1, 00E-12 is equal to 10^{-12}.

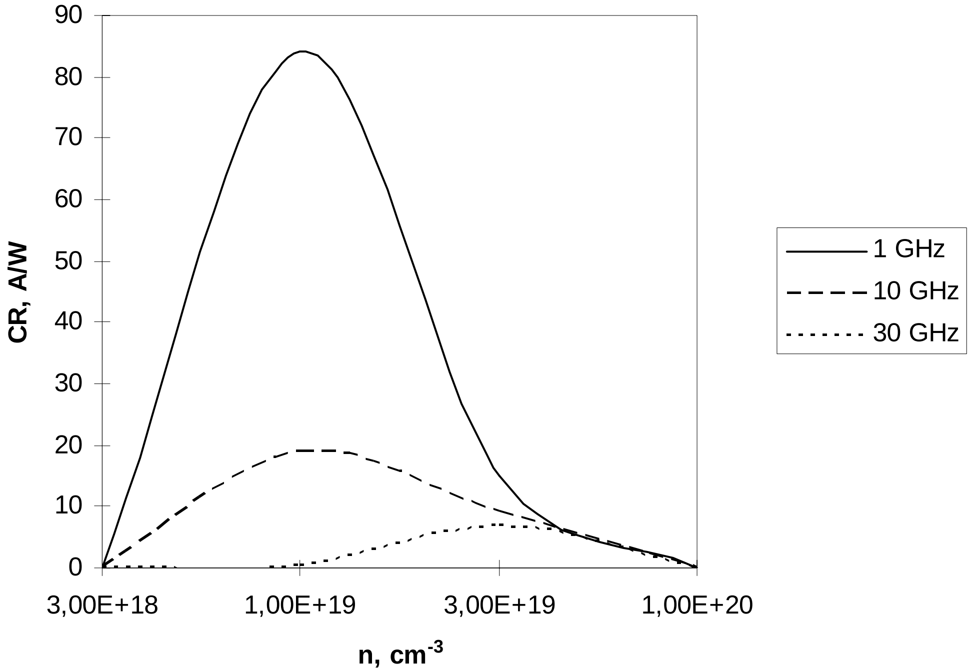

Fig. 1. The calculated current responsivity dependence on the free electron concentrations in silicon. The signal frequency is shown in the figure.

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. Consequently, the current responsivity practically does not depend on the signal frequency when FEC is above 5×10^{19} cm^{-3} and signal frequency is below 30 GHz.

On the other hand, when FEC is lower than 3×10^{18} cm^{-3} the potential barriers are wide. In this situation, the tunneling of electrons near the Fermi level is not important. The main contribution to the current is due to electrons from higher energy levels, where the anomaly of superconductor density of states is negligible.

When FEC rises from 3×10^{18} cm^{-3} to 10^{19} cm^{-3} the potential barriers become narrower, the electrons near the Fermi level join the electric current, both CVD nonlinearity and current responsivity rise.

However, further FEC rise leads to the barrier permeability increase. As a consequence the CVD nonlinearity and current responsivity reduce. In contacts with FEC above 10^{20} cm^{-3} the contact current density can exceed the critical one in HTSC [6] and contacts can become practically ohmic.

2. The frequency characteristics

The calculated current responsivity, voltage responsivity and NEP dependences on the signal frequency are shown in fig. 2, 3 and 4 respectively. In fig. 2 the logarithmic scale for X-axis is used. In figures 3, 4 the double logarithmic scale is used. Taking into account data of Fig. 1 and results of [7, 8] the following FEC are considered: $n=10^{19}$ cm^{-3} for silicon and $n=10^{16}$ cm^{-3} for InSb.

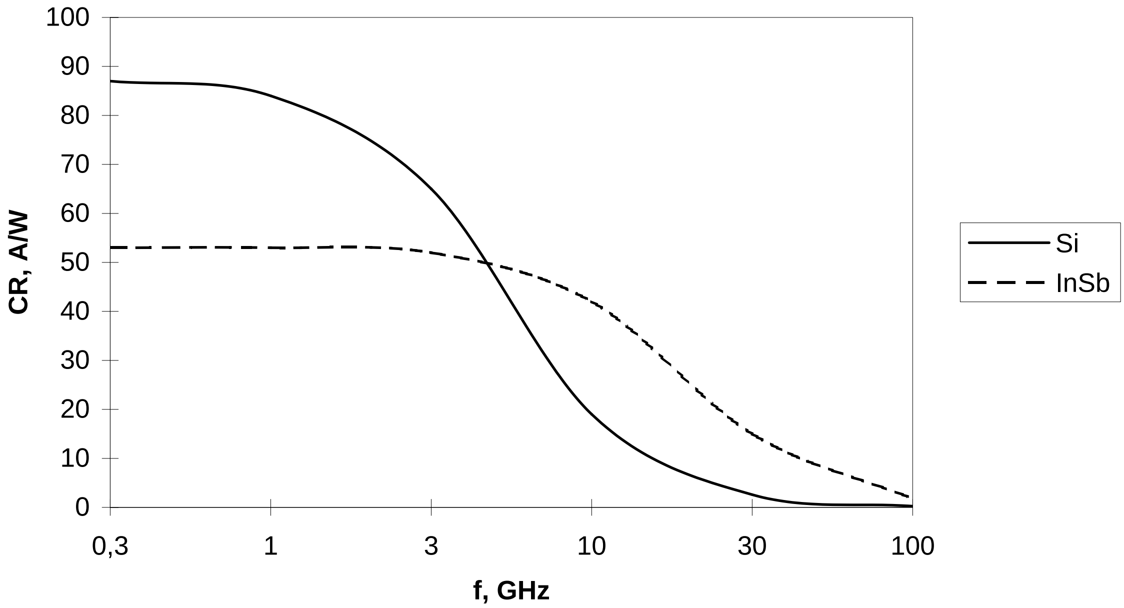

Fig. 2. The calculated current responsivity dependence on the signal frequency.

Figures 2, 3, 4 show that the current and voltage responsivities decrease and NEP increases at the frequencies higher than 3 GHz for silicon and 10 GHz for InSb. 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 comparable with ohmic resistance. The signal power redistribution occurs, it leads to reduction of the rectified current and DD parameters become worse.

In contact with silicon, both barrier capacity and ohmic resistance are higher than in contact with InSb. Consequently, the parameters of contact with silicon get worse at lower frequencies than in contact with InSb.

On the other hand, both working current and noise current in contact with silicon are respectively 600 and 25 times higher than the ones in contact with InSb. Therefore, both voltage responsivity and noise equivalent power in contact with InSb are much better, because it is important to increase voltage responsivity and to decrease noise equivalent power [9]. The physical reasons of this situation are discussed in the next section.

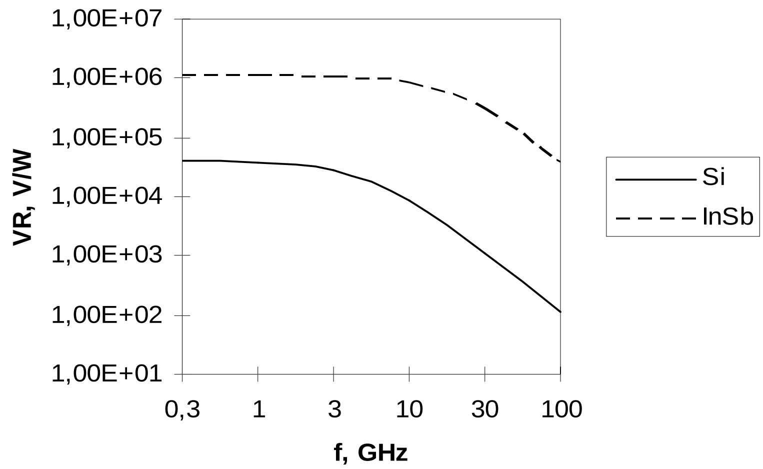

Fig. 3. The calculated voltage responsivity dependence on the signal frequency.

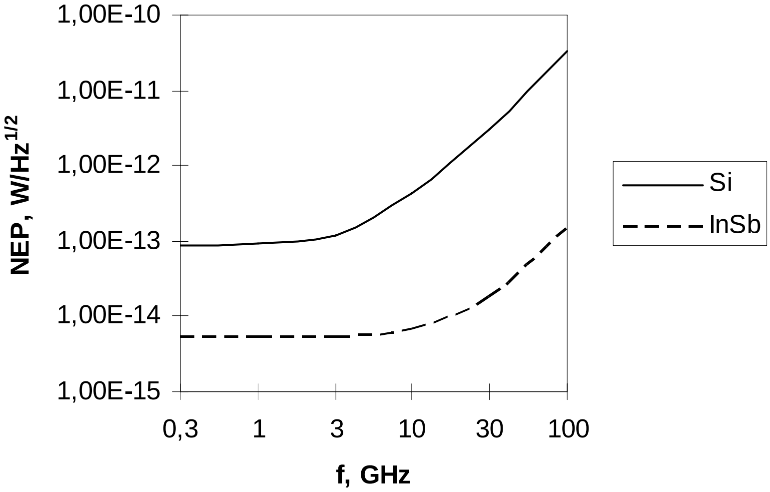

Fig. 4. The calculated noise equivalent power dependence on the signal frequency.

3. Material properties

According to the presented results (Section 1 and data [7, 8]) the optimum barrier permeability should be determined, because both too wide and too narrow barriers make DD parameters worse. On the other hand, for situation, when the barrier permeabilities in contacts with InSb and silicon are approximately equal and WKB approximation is valid, we obtain the following relation between the contact capacities:

$$\frac{C_s}{C_i} \approx \frac{\varepsilon_s}{\varepsilon_i}\sqrt{\frac{\phi_{0s} m_s}{\phi_{0i} m_i}} \qquad (1)$$

Here C is a contact capacity, indexes s and i signify silicon and InSb correspondingly, ε is a relative dielectric permeability ($\varepsilon_s \approx 11.8$, $\varepsilon_i \approx 18$ [10]), ϕ_0 is a surface potential in a semiconductor (according to our calculations $\phi_{0s} \approx 400$ meV and $\phi_{0i} \approx 100$ meV), m is effective mass of electrons in the conduction band to a tunneling direction.

In InSb $m_i = 0.0133\, m_0$, where m_0 is a free electron effective mass, m_i is isotropic [10]. In silicon for direction <111> there is $m_s \approx 0.26\, m_0$ (according to [10, 11] and our calculations). Then we obtain from (1): $C_s / C_i \approx 5.7$, therefore the contact capacity in structures with silicon is larger. The physical explanation is clear: both tunneling effective mass and barrier height in contacts with silicon are higher than in the ones with InSb, therefore the barrier in silicon must be much narrower to acquire a permeability equal to the one in InSb. In this situation the contact capacity grows.

On the other hand in silicon FEC is 3 orders higher than in InSb (see Section 2). But for these concentrations the electron mobility in InSb (at temperature 77.4 K) is 3 orders higher than the one in silicon [12, 13]. Therefore, the ohmic resistances in both materials are practically equal and frequency characteristics are determined by the relation of capacities (see above).

According to [14] the relation

$$|V| < \left|\frac{\Delta}{q}\right| \tag{2}$$

must be realized in superconductor – semiconductor contacts. Here V is a working point voltage applied to contact, 2Δ is energy gap width in superconductor, q is electron charge. In our situation, when the barrier permeabilities in silicon and InSb are approximately equal, both working point current and its high frequency alterations depend sufficiently on the energy density of states in the conduction band of the semiconductor. Taking into account data of [10], we may write the relation:

$$\frac{N(E)_{Si}}{N(E)_{InSb}} = \left(\frac{m^*_{Si}}{m^*_{InSb}}\right)^{3/2}, \tag{3}$$

where E is electron energy calculated from the conduction band bottom, $N(E)$ is the energy density of states, m^* is the effective mass of the density of states. According to [10] it is known: $m^*_{Si} \approx 1.08 m_0$, $m^*_{InSb} \approx 0.013 m_0$. Then we obtain the relation: $\frac{N(E)_{Si}}{N(E)_{InSb}} \approx 750$. The noise current is approximately proportional to square root of the contact current [9]. In this situation it is clear why the current density and noise current in contacts with silicon are sufficiently higher (see Section 2).

On the other hand, the contacts with silicon have their advantages too. Silicon is an elementary semiconductor, and InSb is a semiconductor compound. Usually the compound technology is more complicated. The silicon technology was developed well due to silicon integrated circuits. Silicon is a widespread material, but the components of InSb, antimony (Sb) and especially indium (In) are relatively rare elements [15]. Silicon is a non-toxic material, but antimony is a toxic one [16].

Therefore, if the big current responsivity only must be obtained and a signal frequency is less than 5 GHz, the use of HTSC – silicon contacts may be an optimal choice.

However, if the high voltage responsivity or NEP is required or a signal frequency is higher than 5 GHz, the HTSC – InSb contacts seem to be preferable.

Conclusion

Both HTSC – silicon and HTSC – InSb contacts may be used to prepare DD. The contacts with silicon are optimal to obtain the high current responsivity at the signal frequency less than 5 GHz.

The contacts with InSb are preferable when it is necessary to improve voltage responsivity or NEP or if a signal frequency is higher than 5 GHz. The main advantages of InSb are small effective mass and high mobility of electrons in the conduction band.

The comparison with data of [1, 2] shows that in the proposed DD the voltage responsivity can be 60 times higher and NEP can be 100 times less than the ones in existing devices (at the same temperature and signal frequency). The contact area reduction allows improving of DD characteristics. Taking into account that the high voltage responsivity and low NEP are desirable we may conclude that the HTSC-semiconductor contacts have a good perspective for cryogenic electronics.

Acknowledgement

The author is thankful to Member of Moldavian Academy of Sciences Professor V.G. Kantser for proposed idea of this research.

References

[1] V.A. Kulikov, L.V. Matveets, L.V.Serebryakov et al., Pis'ma v JTF (Letters in Journal of Technical Physics – in Russian), 15, 74, (1989).
[2] L.S. Kuz`min, V.N. Ohrimenko, E.S. Soldatov, A.N. Tavhelidze, Sverhprovodimost` (Superconductivity – in Russian), 3, 2650, (1990).
[3] V.N. Alfeev, L.N. Neustroev, Doclady Akademii Nauk SSSR (Reports of the Soviet Academy of Sciences – in Russian), 312, 81, (1990).
[4] H. Hasegawa, T. Fukazawa, T. Aido, Jap. J. Appl. Phys., Pt. 2, 28, L2210, (1989).
[5] L.D. Chang, M.Z. Tseng, L.A. Sonosca et al., Materials Research Society Spring Meeting. Preliminary Program –USA, Annaheim, 63, 1991.
[6] M.R. Beasley, Proc. IEEE, 77, 1155, (1989).
[7] Ia.I. Kerner, Proc. 8-th Int. Conf. on ternary and multinary compounds, Stiinta, Chisinau, 2, 124, 1990.
[8] Ia.I. Kerner, Proc. 4-th Int. Conf. “Microelectronics and Computer Science”. Elan Poligraf, Chisinau, 149, 2005.
[9] V.I. Striha, E.V. Buzaniova, I.A. Radzievsky, Semiconducting devices with Schottky barrier (in Russian), Sov. Radio, Moscow, 1974.
[10] K.V. Shalimova, Physics of semiconductors (in Russian), Atomic energy, Moscow, 1985.
[11] C.R. Crowell, Solid State Electronics, 12, 55, (1969).
[12] Physical Values Tables (in Russian), Atomic energy, Moscow, 1976.
[13] C. Hilsum, A.C. Rose-Innes, Semiconducting III-V compounds (in Russian), Foreign literature, Moscow, 1963.
[14] V.N. Alfeev, Superconductors, Semiconductors and Paraelectrics in Cryoelectronics (in Russian), Sov. Radio, Moscow, 1979.
[15] N.L. Glinka, Common Chemistry (in Russian), Chemistry, Leningrad, 1979.
[16] Big Soviet Encyclopedia (BSE, in Russian), BSE publishing house, Moscow, 25, 94, 1976.