

UDC 621.315.592
EDN: GUEYLP

PACS: 73.40QV, 73.21AS,
85.60GZ, 73.61GA

Study of surface leakage currents in LWIR nBn HgCdTe photosensitive structure with superlattice barrier

A. V. Voitsekhovskii^{1,*}, S. M. Dzyadukh¹, D. I. Gorn¹, S. A. Dvoretiskii^{1,2}, N. N. Mikhailov^{1,2},
G. Yu. Sidorov² and M. V. Yakushev²

¹ National Research Tomsk State University, Tomsk, 634050 Russia

* E-mail: vav43@mail.tsu.ru

² A. V. Rzhanov Institute of Semiconductor Physics SB RAS, Novosibirsk, 630090 Russia

Received 18.07.2025; revised 4.08.2025; accepted 20.10.2025

The studies of n -B(SL)- n and MI- n -B(SL)- n structures formed on the basis of epitaxial films grown by the MBE method from HgCdTe with a superlattice in the barrier region are carried out. The composition in the absorbing layer of the structures is designed for operation in the LWIR range and was 0.22. Two different superlattice architectures were fabricated and studied. The study of dark currents of n -B(SL)- n structures showed that for both types of samples an anomalous dependence of the current density on temperature is observed with a minimum of the current density at temperatures of 100–120 K. The dominance of the surface leakage current components was revealed for both structures. Based on the study of the admittance of MI- n -B(SL)- n structures, it is shown that the characteristics of the studied structures have a form similar to the characteristics of MIS structures fabricated on the basis of homogeneous $Hg_{0.78}Cd_{0.22}Te$.

Keywords: HgCdTe; molecular beam epitaxy; barrier structure; nBn ; superlattice; surface current.

DOI: 10.51368/2949-561X-2025-5-11-18

Introduction

HgCdTe-based unipolar barrier nBn structures are considered promising for development of infrared (IR) photodetectors for the long-wave infrared (LWIR, 8–14 μm) spectrum that operate at higher cooling temperatures than conventional HgCdTe photodiodes [1]. Among the architectures for barrier photosensitive structures having the high potential there are n -type HgCdTe-based nBn structures grown by molecular beam epitaxy (MBE) [2]. Currently, the most promising configuration is considered to be a structure with a barrier formed as a superlattice (SL) – n -B(SL)- n structures. Modifying the SL parameters (layer compositions and thicknesses) allows for controlling the positions of energy band edges in the barrier layer of the nBn structure and

minimizing discontinuities of energy bands at the absorption layer / barrier / contact layer heterointerfaces [3].

The today's world academic literature offers very few studies devoted to the fabrication and experimental study of HgCdTe-based nBn structures with a SL barrier [4–7]. Most works on HgCdTe-based nBn structures are theoretical and describe the simulation of various heterostructure configurations aimed at reducing dark currents and increasing sensitivity. In particular, there are no works devoted to the study of HgCdTe-based n -B(SL)- n structures tailored to the LWIR range.

Practical implementation of HgCdTe-based n -B(SL)- n structures is hindered not only by fundamental issues (such as non-zero valence-band discontinuity [8]) but also by fabrication challenges. Being designed using theoretical

models structures of this type often exhibit characteristics that do not match theoretical predictions during experimental study. This applies equally to the SL barrier layer parameters determined by experimental data and the experimentally measured dark current values. In particular, the dark current-voltage characteristics (CVC) observed during an experiment are known to be often different from theoretical ones due to the prevalence of surface leakage currents. This mechanism of dark current generation occurs due to the specific features of the fabrication technology for experimental samples, primarily of the technology for depositing a passivation layer on the sample surface. Furthermore, currently there is no satisfactory example of modeling and subsequent experimental verification of an effective superlattice barrier layer for a photosensitive HgCdTe-based nBn structure. One reason for this is the limited number of studies of the development, practical implementation, and experimental study of n -B(SL)- n HgCdTe structures, due to which the sufficient theoretical and experimental data have not been provided so far.

This paper offers two configurations of photosensitive n -HgCdTe-based n -B(SL)- n structures with a superlattice in the barrier region for the LWIR range. Parameters of the superlattice barrier layers were selected based on theoretical assessments to achieve the maximum possible barrier height for majority charge carriers in the conduction band and the minimum barrier size for minority charge carriers.

This work is dedicated to analyzing the current generation mechanisms in two different LWIR nBn HgCdTe structures with a superlattice in the barrier region.

Experimental Samples and Methods

Two types of HgCdTe epitaxial films were grown on GaAs (013) substrates. The films were grown at the Institute of Semiconductor Physics, Siberian Branch of the Russian Academy of Sciences, using "Ob-M" molecular beam epitaxy system. To align the structure's epitaxial layers with the substrate, buffer layers of ZnTe ($\sim 0.3 \mu\text{m}$ thick) and CdTe ($\geq 5.5 \mu\text{m}$ thick) were first grown on substrate surface. This was followed by the sequential growth of the HgCdTe graded-gap base with its composition changing from 0.28 at

the interface with CdTe to ~ 0.22 , which corresponded to the composition of the absorbing layer, which was $\sim 5.5 \mu\text{m}$ thick.

After that a superlattice that acted as a barrier layer was grown, with a contact layer with a composition of ~ 0.22 of $\sim 0.5 \mu\text{m}$ in thickness formed on its surface. The films differed in the parameters of their superlattice layers. The superlattice of structure No. 1 consisted of 15 wells, each 12 nm wide, and 16 barriers, each 8 nm wide. The superlattice of structure No. 2 consisted of 15 wells, each 4 nm wide, and 16 barriers, each 8 nm wide. The grown HgCdTe film was intentionally not doped. After being growth, the epitaxial film was etched through a special mask to a depth corresponding to the interface position between the absorbing and barrier layers. As a result, standalone nBn structures (mesastructures) with diameters ranging from 0.50 mm to 0.02 mm were formed on the film surface.

To study the current characteristics and admittance, two types of experimental samples were fabricated based on the grown epitaxial films: a version with indium electrodes deposited directly on the contact layer (n -B(SL)- n structure) and a metal-insulator-semiconductor (MIS) version where the electrodes were separated from the contact layer by a functional dielectric layer (MI- n -B(SL)- n structure). Both structure types featured passivation of the entire non-metallized surface of the epitaxial film with Al_2O_3 dielectric deposited by the plasma-enhanced atomic layer deposition (PE ALD) procedure.

The studies were conducted using an automated heterostructure admittance spectroscopy system which included Keithley 6487 picoammeter, a cryogenic temperature control system, and a vacuum system. This system is capable of maintaining a stable temperature of the sample stage within the range of 11 K to 475 K for extended periods, with a temperature control accuracy not worse than 0.2 K.

Results and their discussion

Figure 1a shows the current density vs. bias voltage dependencies for mesastructures of various diameters at the temperature of 80 K derived for Structure No. 1. As can be seen in the figure the current density at a fixed bias voltage

increases as the mesastructure diameter decreases. To determine the bulk and surface current components, curves of the current density vs. the ratio of mesastructure's perimeter P to

mesastructure's area A at the bias voltage of $+0.2$ V. These curves are shown in Figure 1b. As can be seen in the figure this type of structure features high surface leakage current densities.

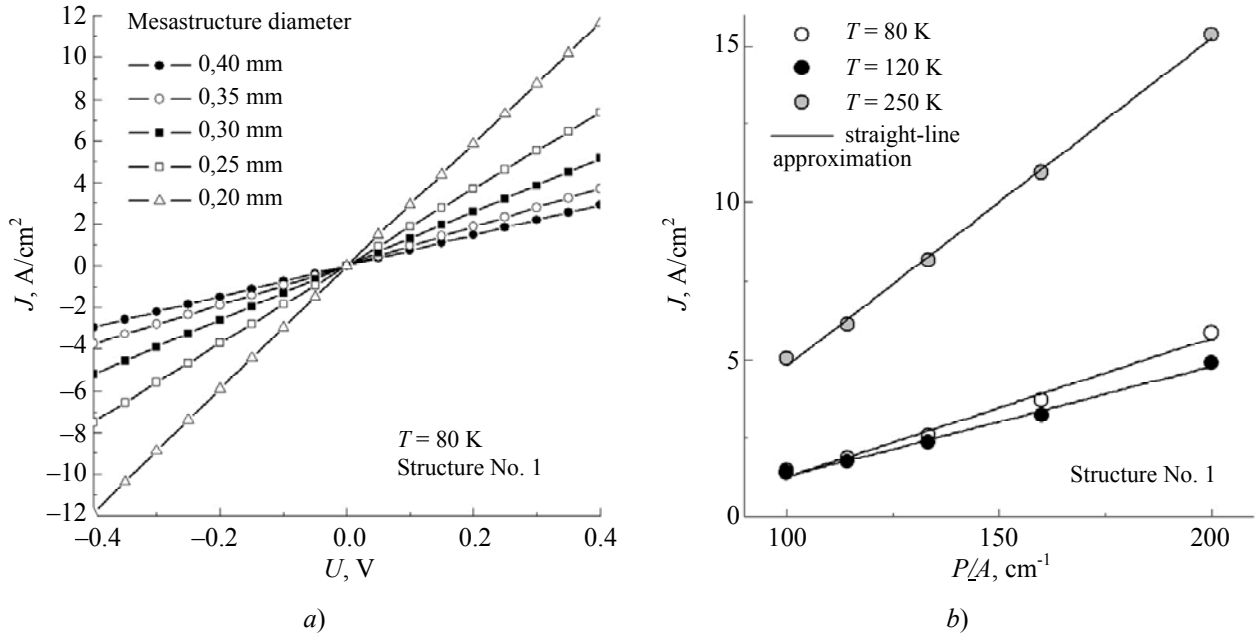


Fig. 1. Current density J vs. bias voltage U for mesastructures of various diameters at the temperature of 80 K (a), and current density vs. P/A ratio at various temperatures at $U = +0.2$ V (b) for Structure No. 1

Figure 12a shows current densities vs. voltage dependencies for structures of various diameters at the temperature of 80 K derived for Structure No. 2. This structure can be seen to be also prone to significant increase of current density as the mesastructure diameter decreases at

the fixed bias voltage, which indicates a surface leakage current component of considerable magnitude. The plotted curves of current density vs. the ratio of the structure's perimeter to the structure's area at the bias voltage of $+0.2$ V for Structure No. 2 are shown in Figure 2b.

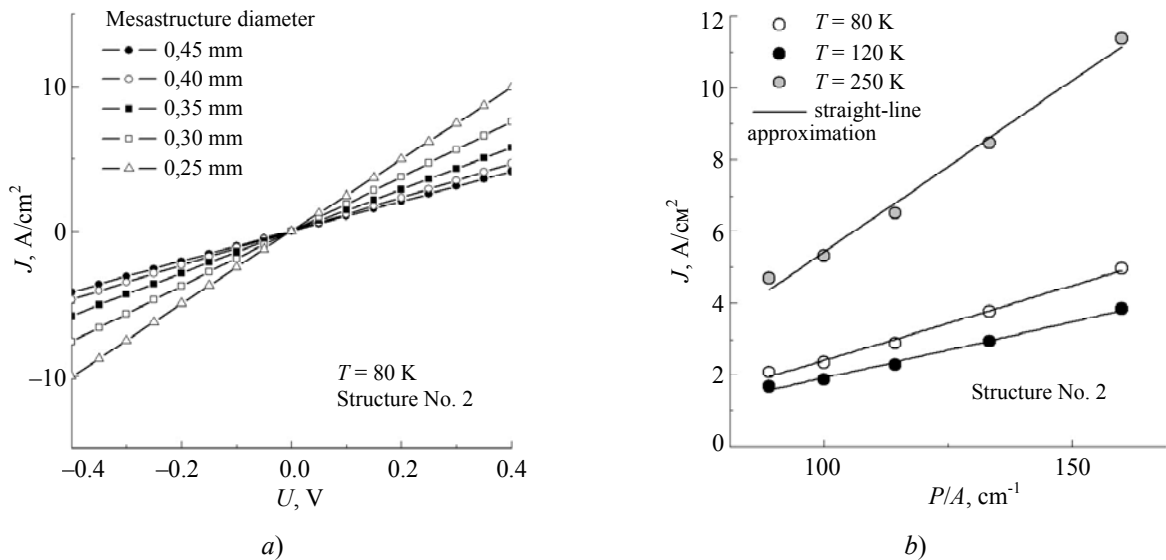


Fig. 2. Current density J vs. bias voltage U for mesastructures of various diameters at the temperature of 80 K (a), and current density vs. P/A ratio at various temperatures at $U = +0.2$ V (b) for Structure No. 2

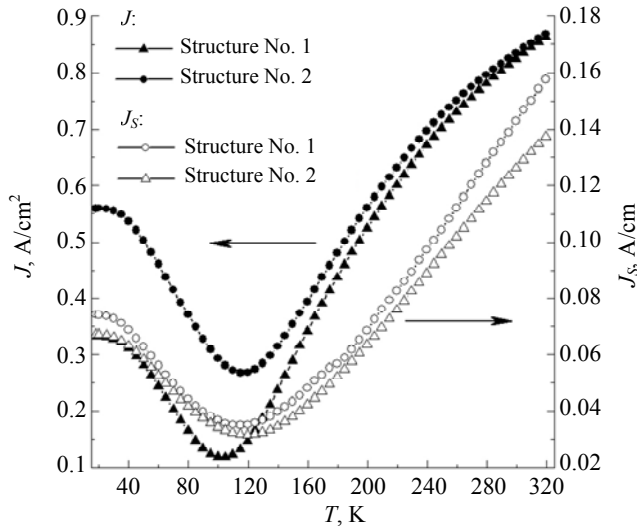


Fig. 3. Total current density J (for a mesastructure with a diameter of 0.4 mm) and surface leakage current density J_s vs. temperature T at the bias voltage of +0.2 V for Structures No. 1 and No. 2

Figure 3 shows the curves of total current density (mesastructure diameter of 0.4 mm) and surface leakage current density vs. sample temperature derived from the slopes of the curves of current density vs. the ratio of structure's perimeter P to structure's area A at various temperatures for Structures No. 1 and No. 2. An anomalous temperature dependence of current density can be seen in the figure for this sample type. These curves show the minimum current density at temperatures of 100–120 K. For mesastructures of various diameters made of the same epitaxial film, positions of the minima coincide. However, the minima occur at various temperatures for structures made of film No. 1 and film No. 2. The curves of surface leakage current density vs. sample temperature also show a minimum, but in this case the minima for Structures No. 1 and No. 2 practically coincide. The values of surface leakage current components at similar temperatures obtained for the studied samples approach each other. The maximum difference in current density values across the entire temperature range studied does not exceed 15 %. This allows concluding that the structure passivation technology exhibits good stability. It is not feasible to determine the bulk current component due to the prevailing surface leakage current component, which makes further direct current studies uninformative.

In such a situation, the admittance spectroscopy method [9] is well suited

for analyzing the fabricated structures. The equivalent circuits method was used to process the admittance measurements. The equivalent circuits and formulas for determining the series resistance can be found in reference [10]. Figure 4 shows the curves for the reciprocal of series resistance R_s of the epitaxial film volume, extracted from the admittance measurements using the equivalent circuits method, vs. temperature for Structures No. 1 and No. 2, with mesastructure diameters being 0.35 mm. The data were obtained at the frequency of 1 MHz in the enhancement mode. The figure shows that the temperature curves of $1/R_s$ for samples No. 1 and No. 2 are qualitatively similar to those of the surface leakage current components.

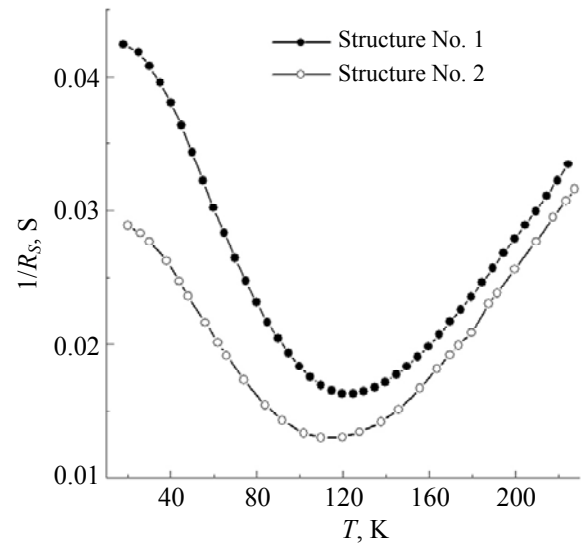


Fig. 4. $1/R_s$ value vs. temperature for Structures No. 1 and No. 2 with mesastructure diameters of 0.35 mm at the frequency of 1 MHz

Figures 5a and 5b show capacitance-voltage (C-V) curves of Structures No. 1 and No. 2 with a mesastructure diameter of 0.5 mm as measured at the temperature of 15 K. Here, C is the electrical capacitance. Measurements were made at identical bias voltage sweep rates and directions. The series resistance of the epitaxial film volume has been excluded from the measurement results. As can be seen in the figures, the flat-band voltage for the first structure has a value approaching the zero bias voltage. This means that these structures do not have any significant fixed charge in the dielectric coating. However, the flat-band voltage for sample No. 2 has a positive value and is greater in magnitude than that for sample No. 1.

Concentration of majority charge carriers for sample No. 1 as determined from the slope of the squared capacitance reciprocal in the depletion mode at the frequency of 1 MHz, was $1,24 \times 10^{21} \text{ m}^{-3}$. In the temperature range from 15 K to 150 K, this yields the maximum width of the space-charge region (SCR) of $3.80 \times 10^{-7} \text{ m}$ to $2.18 \times 10^{-7} \text{ m}$. Since the contact layer thickness of $5.0 \times 10^{-7} \text{ m}$, it means that the space-charge region does not reach the barrier layer with the superlattice. In terms of the equivalent circuits

model, this means the barrier layer impacts only the series resistance of the epitaxial film volume. Concentration of majority charge carriers for sample No. 2 as determined under the same conditions was $7.65 \times 10^{20} \text{ m}^{-3}$. In the temperature range from 15 K to 120 K, this yields a maximum SCR width of $4.80 \times 10^{-7} \text{ m}$ to $2.28 \times 10^{-7} \text{ m}$. This indicates that SCR for this sample does not reach the superlattice barrier layer either, but only approaches its boundary at the temperature of 15 K.

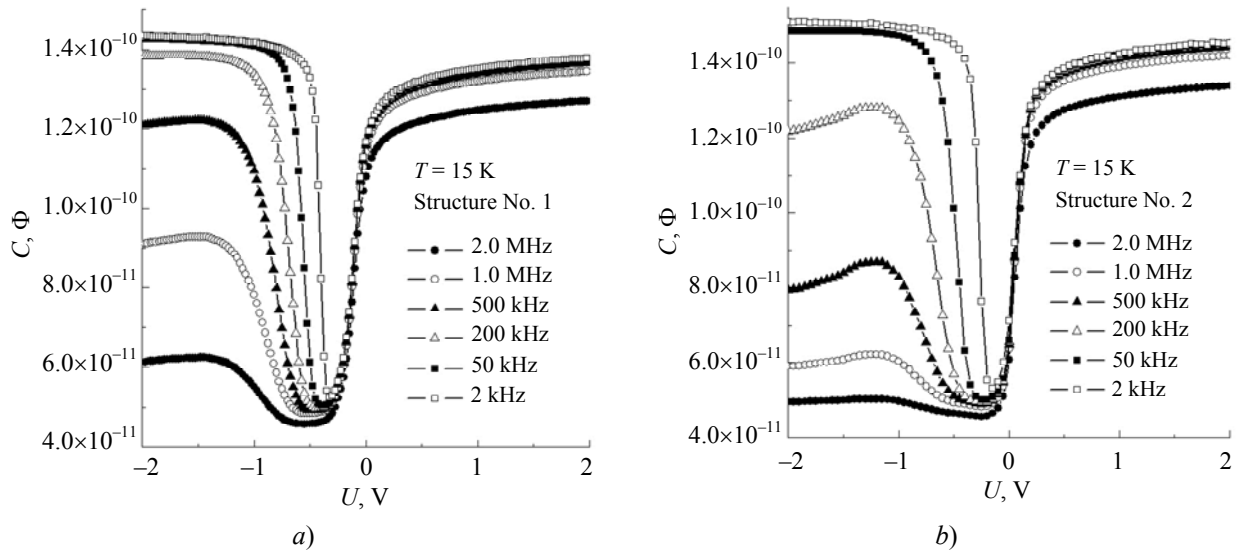


Fig. 5. *C-V curve for Structure No. 1 (a) and Structure No. 2 (b) at the temperature of 15 K as measured with forward voltage sweep*

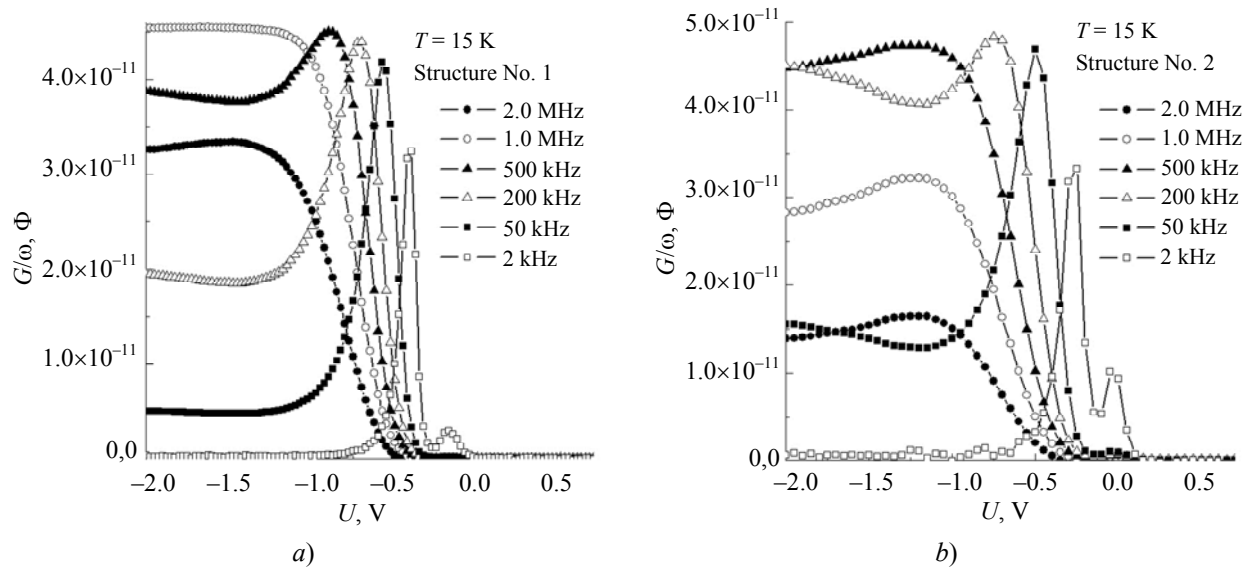


Fig. 6. *Differential conductance for Structure No. 1 (a) and Structure No. 2 (b) vs. the bias voltage at the temperature of 15 K as measured with forward voltage sweep*

Figure 6 shows the curves of differential conductance for Structures No.1 and No.2 as measured at the temperature of 15 K. The series

resistance of the epitaxial film volume has also been excluded from the measurement results in the figures shown. The curves of differential

conductance vs. the bias voltage for Structures No. 1 and No. 2 exhibit a peak in the bias voltage region corresponding to the depletion mode, which is associated with the occurrence of the density typical of fast surface states. Their occurrence is due to the absence of a near-surface graded-gap base.

The study of the C-V curves as measured in forward and reverse directions of bias voltage sweep showed that the curves of both structures exhibit minor hysteresis. This indicates a low density of slow surface states; however, the density of surface states for Structure No. 2 is still somewhat higher than for Structure No. 1. Another common feature for both structures is that the hysteresis does not show significant change in the capacitance level at the minimum of the C-V curve, which is typical of structures without a near-surface graded-gap base.

Figure 7 shows the curves of R_{DA} vs. reciprocal temperature obtained in strong inversion mode (at the bias voltage of -2 V) at the frequency of 1 MHz for samples No. 1 and No. 2. As can be seen in the figure, the SCR resistance of the structures at low temperatures is limited by interband tunneling, while at higher temperatures, R_{DA} is limited by diffusion of minority charge carriers from the quasi-neutral region. R_{DA} values for Structure No. 2 are higher than for Structure No. 1, reaching the value of approximately $12.4 \Omega \cdot \text{cm}^2$ at the maximum. The higher values of R_{DA} in major inversion mode for Structure No. 2 are also confirmed by C-V curve measurements, which exhibit higher frequencies relative to the inversion layer formation time under the same conditions for Structure No. 2.

According to the equivalent circuits method, the series resistance of the epitaxial film volume bears the information about the part of the semiconductor film in the MIS structure which is not included in SCR. Derived from the slope of the curve of the volume resistance reciprocal logarithm vs. $q/(k_B \times T)$ at various frequencies of the alternating test signal were the values of charge carrier activation energy for samples No. 1 and No. 2 provided that they are generated in interband conditions. The curve of the activation energy, which is determined from the temperature vs. series resistance curve, vs. frequency of the alternating test signal is shown in Figure 8. As the frequency increases, the determined activation

energy grows linearly in the frequency range from 500 kHz to 2 MHz. It is difficult to interpret such results at this stage and further research is required. However, it should be noted that the activation energy value obtained for sample No. 1 at the 1 MHz frequency is 72 meV, which is more than two times as low as the bandgap energy for HgCdTe with composition $x = 0.22$ in this temperature range ($E_g \approx 0.158 \text{ eV}$). The activation energy value obtained under the same conditions for sample No. 2 is 147 meV, which is quite close to the bandgap energy for HgCdTe with composition $x = 0.22$. The results presented allow concluding that sample No. 1, unlike sample No. 2, features the energy level within the bandgap. This energy level is derived at high temperatures using the series resistance vs. temperature curve and accounts for the lower differential resistance.

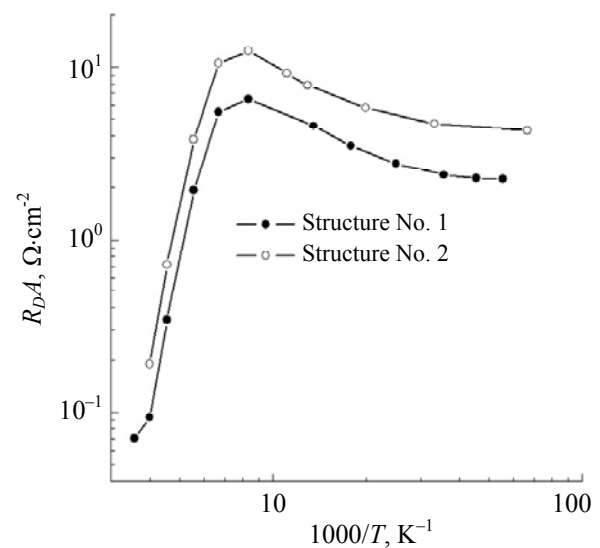


Fig. 7. Curves of R_{DA} vs. reciprocal temperature obtained in strong inversion at the frequency of 1 MHz for samples No. 1 and No. 2

The presence of mesastructures with various cross-sectional areas on the experimental samples allows for plotting the curve of the reciprocal series resistance of the epitaxial film volume R_S vs. the ratio of mesastructure perimeter R_S to mesastructure area A . Figure 9 shows these curves plotted at different frequencies for sample No. 2. As can be seen in the figure, the curve behavior is compliant with the idea that as the P/A ratio increases, the conductance grows due to the mechanisms associated with current flow over the surface.

Straight-line approximation of these curves allows estimating the conductance component associated with surface leakage based on the curve slope.

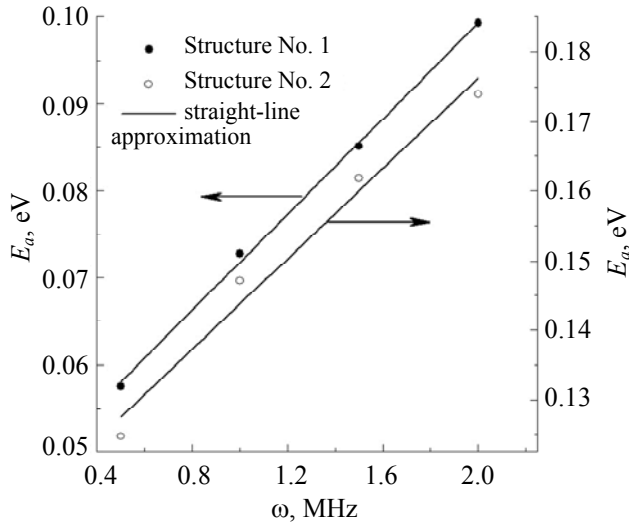


Fig. 8. Determined activation energy E_a vs. alternating test signal frequency ω for samples No. 1 and No. 2

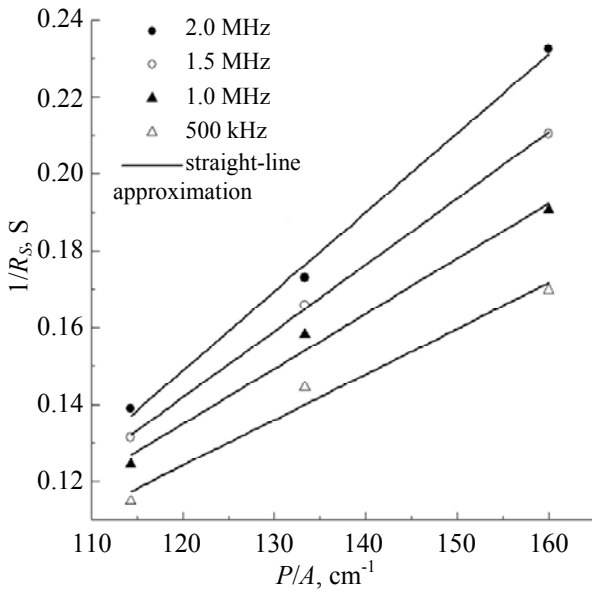


Fig. 9. $1/R_s$ vs. the P/A ratio at various frequencies of the alternating test signal

Figure 10 shows the curves of the conductance component associated with surface current flow processes vs. alternating test signal frequency which are plotted using the slope of the straight-line approximated curves of $1/R_s(P/A)$. As can be seen in the figure, the surface conductance values for sample No. 1 are frequently in excess of the conductance values for sample No. 2 across the entire frequency range studied. This observation correlates to the data

shown in Figure 7 and links lower R_{DA} value of sample No. 1, in part, to its higher surface leakage current.

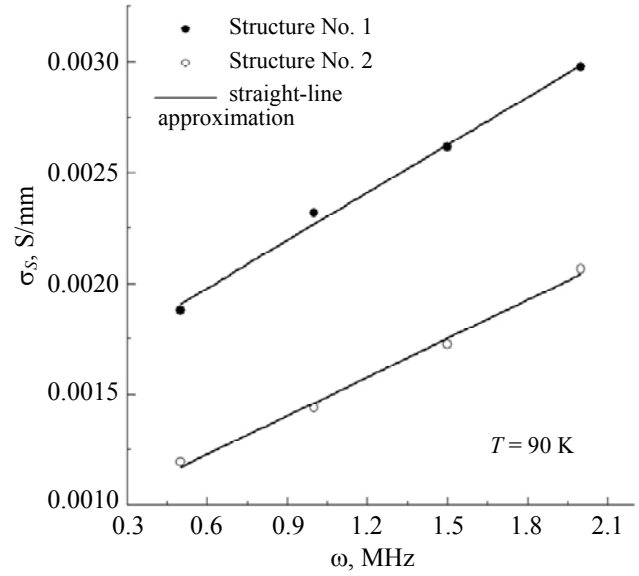


Fig. 10. Surface conductance σ_s vs. alternating test signal frequency ω at the temperature of 90 K

Conclusion

This paper presents the findings of the study of n -B(SL)- n and MI- n -B(SL)- n structures formed from epitaxial films grown by the MBE method from the three-component semiconductor HgCdTe with a superlattice in the barrier region. The composition of the structures' absorbing layer is designed for operation in the LWIR range and was 0.22.

The study of dark currents of the n -B(SL)- n structures revealed that both sample types exhibit an anomalous temperature vs. current density curves, with the current density minimum at temperatures of 100–120 K. The curves of temperature vs. surface leakage current components, as well as the total dark current density, also exhibit minima. Additionally, the study showed that Structure No. 1 features a larger surface leakage current component across the entire temperature range studied.

The admittance spectroscopy studies performed allow concluding that characteristics of the analyzed structures generally resemble those of MIS structures made of homogeneous $\text{Hg}_{0.78}\text{Cd}_{0.22}\text{Te}$. A low density of slow surface states is typical of these structures, which is well illustrated by the plotted C-V curves of the

structures studied. The R_{DA} vs. temperature curves show the interband tunneling occurring at low temperatures, which is also typical of MIS structures based on homogeneous HgCdTe with a composition of 0.2 and without a graded-gap base. Lower R_{DA} values for sample No. 1 compared to sample No. 2 are likely due, in part, to its higher surface leakage current values. The fact that the activation energy of sample No. 1 derived from the curve of temperature vs. epitaxial film series resistance is approximately twice as low as the band gap width indicates the presence of generation centers for free charge carriers within the band gap. The activation energy value for

sample No. 2 is quite close to the band gap value for HgCdTe with composition $x = 0.22$. The curves of surface leakage current densities and reciprocal series resistance of the epitaxial film volume vs. temperature are qualitatively similar. The reasons for the strong dependence of the samples' activation energy vs. frequency cannot be interpreted at this stage of the study and require further studying.

The study was supported by a grant from the Russian Science Foundation No. 23-62-10021, <https://rscf.ru/project/23-62-10021/>.

REFERENCES

1. Shi Q., Zhang S.-K., Wang J.-L. and Chu J.-H., J. Infrared Millim. Waves. **41** (1), 139–150 (2022).
2. Voitsekhovskii A. V., Nesmelov S. N., Dzyadukh S. M., Gorn D. I., Dvoretzky S. A., Mikhailov N. N., Sidorov G. Y. Ch. 6, II-VI Semiconductor-Based Unipolar Barrier Structures for Infrared Photodetector Arrays in Handbook of II-VI Semiconductor-Based Sensors and Radiation Detectors. Cham. Springer, 2023. P. 135–154.
3. Kopytko M., Wrobel J., Jozwikowska K., Rogalski A., Antoszewski J., Akhavan N. D., Umana-Membreno G. A., Faraone L. and Becker C. R., Journal of Electronic Materials **44** (1), 158–166 (2015).
4. Benyahia D., Martyniuk P., Kopytko M., Antoszewski J., Gawron W., Madejczyk P., Rutkowski J., Gu R. and Faraone L., Opt Quant Electron. **48**, 215 (2016).
5. Izhnin I. I., Kurbanov K. R., Voitsekhovskii A. V., Nesmelov S. N., Dzyadukh S. M., Dvoretzky S. A., Mikhailov N. N., Sidorov G. Y. and Yakushev M. V., Applied Nanoscience. No. 10, 4571–4576 (2020).
6. Voitsekhovskii A. V., Dzyadukh S. M., Gorn D. I., Dvoretzky S. A., Mikhailov N. N., Sidorov G. Yu. and Yakushev M. V., Journal of Communications Technology and Electronics **68** (2), S132–S137 (2023).
7. Sellers R., Man P., Khalidi Z. El., Ahmad Z., Zangeneh D., Grein C., Krishnamurthy S., Hahn S.-R., Mlynarski T. and Sivananthan S., J. Appl. Phys. **137**, 084502 (2025).
8. Voitsekhovskii A. V., Dzyadukh S. M., Gorn D. I., Mikhailov N. N., Dvoretzky S. A., Sidorov G. Yu. and Yakushev M. V., Journal of Optical Technology **91** (2), 67–76 (2024).
9. Zubkov V. I., Yakovlev I. N., Litvinov V. G., Ermachihin A. V., Kucherova O. V. and Cherkasova V. N., Semiconductors **48**, 917–923 (2014).
10. Voitsekhovskii A. V., Nesmelov S. N. and Dzyadukh S. M., Russian Physics Journal **48** (6), 584–591 (2005).

About authors

Voytsekhovskii Alexander Vasilyevich, Dr. Sci. (Phys.-Math.), Chief Research Scientist, National Research Tomsk State University (634050, Russia, Tomsk, 36 Prospekt Lenina). E-mail: vav43@mail.tsu.ru SPIN code: 2257-4512, AuthorID: 4641

Dzyadukh Stanislav Mikhailovich, Cand. Sci. (Phys.-Math.), Research Scientist, National Research Tomsk State University (634050, Russia, Tomsk, 36 Prospekt Lenina). E-mail: bonespirit@mail2000.ru SPIN code: 5292-6000, AuthorID: 571424

Gorn Dmitry Igorevich, Cand. Sci. (Phys.-Math.), Head of Laboratory, National Research Tomsk State University (634050, Russia, Tomsk, 36 Prospekt Lenina). E-mail: gorn.di@gmail.com SPIN code: 4514-3163, AuthorID: 724442

Dvoretzky Sergey Alekseyevich, Cand. Sci. (Phys.-Math.), Senior Research Scientist, National Research Tomsk State University (634050, Russia, Tomsk, 36 Prospekt Lenina). Rzhzanov Institute of Semiconductor Physics, Siberian Branch of the Russian Academy of Sciences (630090, Russia, Novosibirsk, 13 Prospekt Academician Lavrentiev). E-mail: dvor@isp.nsc.ru SPIN code: 8129-7857, AuthorID: 20787

Mikhailov Nikolay Nikolayevich, Cand. Sci. (Phys.-Math.), Senior Research Scientist, National Research Tomsk State University (634050, Russia, Tomsk, 36 Prospekt Lenina). Rzhzanov Institute of Semiconductor Physics, Siberian Branch of the Russian Academy of Sciences (630090, Russia, Novosibirsk, 13 Prospekt Academician Lavrentiev). E-mail: mikhailov@isp.nsc.ru SPIN code: 3449-3155, AuthorID: 107682

Sidorov Georgy Yuryevich, Cand. Sci. (Phys.-Math.), Deputy Director, A. V. Rzhzanov Institute of Semiconductor Physics SB RAS (630090, Russia, Novosibirsk, 13 Prospekt Academician Lavrentiev). E-mail: george@isp.nsc.ru SPIN code: 2965-0930, AuthorID: 551326

Yakushev Maxim Vitalyevich, Dr. Sci. (Phys.-Math.), Deputy Director, A. V. Rzhzanov Institute of Semiconductor Physics SB RAS (630090, Russia, Novosibirsk, 13 Prospekt Academician Lavrentiev). E-mail: yakushev@isp.nsc.ru SPIN code: 2025-2315, AuthorID: 33282