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Article *in* Radiophysics and Quantum Electronics · July 2017

DOI: 10.1007/s11141-017-9741-y

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DOI 10.1007/s11141-017-9741-y
Radiophysics and Quantum Electronics, Vol. 59, No. 8–9, January–February, 2017
(Russian Original Vol. 59, No. 8–9, August–September, 2016)

MICROWAVE COOLED MICROBOLOMETERS BASED ON CERMET Si–Cr FILMS

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UDC 537.311.322

We present the results of creating a cooled microbolometer based on the cermet films of the silicon and chromium mixture. This material is used for manufacturing the freely hanging high-resistive microbolometers for the first time. The details of fabricating such microbolometers and the prospects for using cermet films to construct microbolometers are discussed. The first estimates of sensitivity of the fabricated microbolometers are given.

1. INTRODUCTION

The studies on developing uncooled silicon-based microbolometers (microbolometer matrices) operating at room temperature have been carried out since 1970s [1]. However, despite all the efforts towards developing the silicon bolometers based on alpha silicon [2], the silicon–germanium mixture [3], or germanium [4, 5], and, in recent years, the silicon–germanium mixture doped by boron [6] or iron [7], the parameters and stability of the "room" bolometers based on vanadium oxide [8] still remain the best. Nevertheless, seeking components for the silicon bolometers and the silicon-doping methods is still underway. This is explained by the fact that such bolometers should be easy to manufacture and comparatively cheap. In addition, it seems possible to ensure stability and high sensitivity of the silicon-based microbolometers.

The Si–Cr_x cermets are well known in microelectronics as resistive alloys which are used as materials for manufacturing resistors with low temperature resistance coefficient (TRC) [9]. However, varying the methods of forming thin films, one can obtain a material with a high TRC, e.g., the Si–Nb_x films [10, 11]. We have already discussed the method for manufacturing the Si–Cr_x films and shown the possibility of obtaining the films whose resistance exponentially increases with decreasing temperature. In this case, the TRC increases with decreasing temperature and the "working" point of the film can be controlled by varying the chromium density in this alloy. In the present work, we develop this concept and propose a base model for the microbolometer construction.

2. MANUFACTURING PROCEDURE

The resistive Si–Cr_x films are obtained by the method of magnetron sputtering from two targets, and a more detailed manufacturing-process description is given in [12]. It should be noted that the Si–Cr_x film at the working point (with a TRC of no less than 0.1) has a high surface resistance from 10 to 1000 MΩ per

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square. However, it is well known that the optimum bolometer resistance at the working point amounts to 0.1–1 MΩ. Such a bolometer resistance allows one to use the standard measurement techniques. Therefore, it is required to manufacture a bolometer with a low absolute resistance from a film with a high surface resistance. Actually, to reach the required absolute-resistance value, we should reduce the bolometer area (in squares).

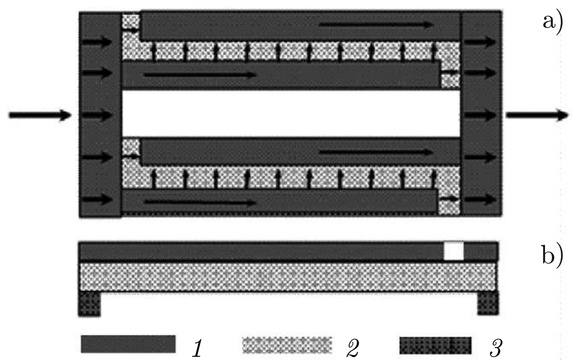

Fig. 1. Layout of a part of the freely hanging microbolometer: top (*a*) and side (*b*) views. The measurement-current direction schematically shown by arrows), absorber (*1*), resistive film (*2*), and photoresist (*3*).

To solve this problem, we propose to use surface shunting of the high-resistivity film by a well-conducting material. The same material (with the same geometry) can be used as the absorbing layer for the received signal. We used a conducting material with a surface resistivity of about 350 Ω per square, which corresponds to the wave impedance of free space. The interdigital structure (see Fig. 1) is an optimal geometry of the conducting layer, which simultaneously ensures absorption and shunting. Actually, we form a high-resistivity thermometer with an absorber, which can rather effectively absorb microwave radiation over the entire frequency range. Antenna is not used for this simplest bolometer geometry. At low temperatures, the microbolometer resistance is determined by the high-resistivity thermoresistive material, which is present on the exposed (non-metallized) areas. For the considered geometry, the total area of the exposed high-resistivity Si–Cr_x film is about 1/20 of a square (without allowance for the spreading resistance).

Irrespective of the properties of the thermal-resistive film, the bolometer properties are basically determined by its architecture. To create a high-sensitivity bolometer, one should ensure the maximum thermal insulation of the absorber. The formation of a freely hanging microbolometer is the simplest method of such thermal insulation. In this case, the bolometer thermal capacity is minimum because of the absence of thermal coupling with the substrate. In this case, the bolometer should be in vacuum to avoid thermal loss during interaction with the surrounding medium via air. It is well known that a freely hanging micron-size bridge can be made if the ratio of the width of the bridge to its length does not exceed 1/10. In the considered case, the microbridge width and length are 10 and about 100 μm, respectively. To reduce the resistance, we formed seven parallel microbridges, which additionally reduces the bolometer resistance by almost an order of magnitude.

To construct a freely hanging microbolometer, a glass-ceramic substrates were used. They were coated by an AZ4562 photoresist with a thickness of about 6 μm, which was used as a sacrifice layer. The photoresist layer is required for cutting and hanging the sensitive part of the microbolometer. The photoresist layer was thermally treated at 180°C to make it insensitive to the developer (i.e., avoid dissolution) during the further photolithographic operations with the subsequent layers.

The Ta_2O_5 and Si–Cr_x films with an each-layer thickness of 100 nm were successively applied to the photoresist by the method of magnetron sputtering. The dielectric sublayer of Ta_2O_5 is used to support the thermoresistive layer and ensure upward bending of the microbridge. The second stage involved the electrode connection to the resistive element and the absorption-layer application. To simplify the manufacturing methods, the electrodes and the absorbing layer were made of the same material in one processing cycle using the lift-off method. The $Si_{0.5}$–$Cr_{0.5}$ alloy with a thickness of about 100 nm and a surface resistivity of about 350 Ω per square was used as the absorber and electrode material. Then the entire structure of the finite-structure geometry was etched using the Ar^+ ions. This operation yielded a system of microbridges located on the photoresist, such that each microbridge had the interdigital structure of the absorber (see Fig. 2).

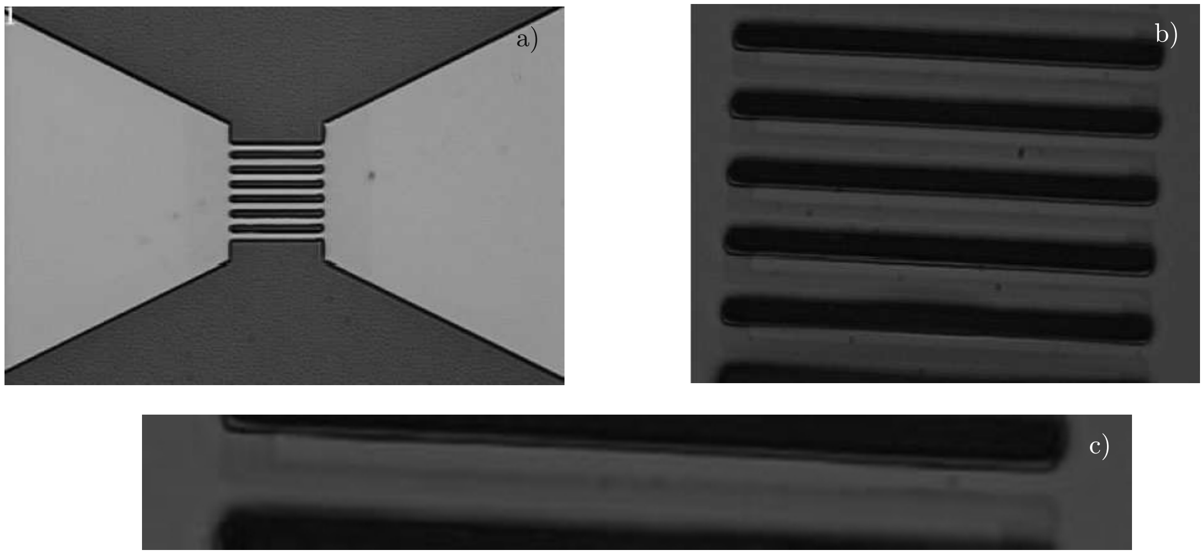

Fig. 2. Photograph of the manufactured microbolometer: general view (*a*), view of the central part (*b*), and the freely hanging microbridge (*c*).

The final step in forming the freely hanging bolometer involved removal of the sacrifice layer of the photoresist under the microbridges. This operation was performed using the high-frequency (HF) generator of the inductively coupled plasma with a power of 300 W, which formed an isotropic plasma with the O_2^+ ions at the working oxygen pressure $5 \cdot 10^{-4}$ Torr in the chamber. The end of the photoresist-etching process under the bridge was visually monitored by the presence of the photoresist “neck” under the bridge with the help of a microscope with a magnification of 500–1000. The etching time of the exposed photoresist regions with a thickness of 6 μm was about 5 min and the time of removal of the resist under the bridge could reach 40–60 min. This delay of the isotropic etching process can be caused by the fact that the Ta_2O_5/ Si–Cr_x film edges turn toward the substrate, thereby contributing to the blocking of the plasma-chemical etching of the photoresist. The final structure is presented in Fig. 2.

3. EXPERIMENTAL TECHNIQUE

The manufactured microbolometers were characterized in a dry cryostat with a basic temperature of 2.7 K, which was manufactured on the basis of “Pulse Tube” refrigerator. The resistive heaters which were located on the cooled massive copper step allowed one to stabilize the temperature. The temperature was controlled by a commercial PT450 sensor with the temperature controller manufactured by the “Lackeshore” company. This stage of work was aimed at manufacturing the microbolometer model with working temperature close to that of liquid nitrogen (about 77 K). In what follows, it could allow one to work with a liquid nitrogen cryostat.

Intrinsic noise of the voltage of the first cascade in the measurement-circuit amplifiers was measured before studying the noise characteristics of the bolometer.

The noise spectral density of the used amplifier with the short-circuited input was about 5 nV/Hz$^{1/2}$ (see Fig. 3). The pink-noise contribution up to the frequencies 60–70 Hz is well seen in this figure. The pink-noise presence is mainly related to the contribution from the amplifier. The theoretical estimate (by the Nyquist formula) of the spectral density of the thermal noise of the bolometer with a resistance of about 17 kΩ at room temperature amounts to 16 nV/Hz$^{1/2}$, which is in good agreement with the experimental results (see Fig. 3) and confirms the correctness of the noise measurements.

It should be noted that intrinsic noise of the amplifier is not restricted to the voltage noise alone. The resulting noise has the component of the current noise of the amplifier, which is equal to $I_N R_l$, where R_l is the load resistance and I_N is the amplifier noise current. Therefore, once the bolometer is cooled to

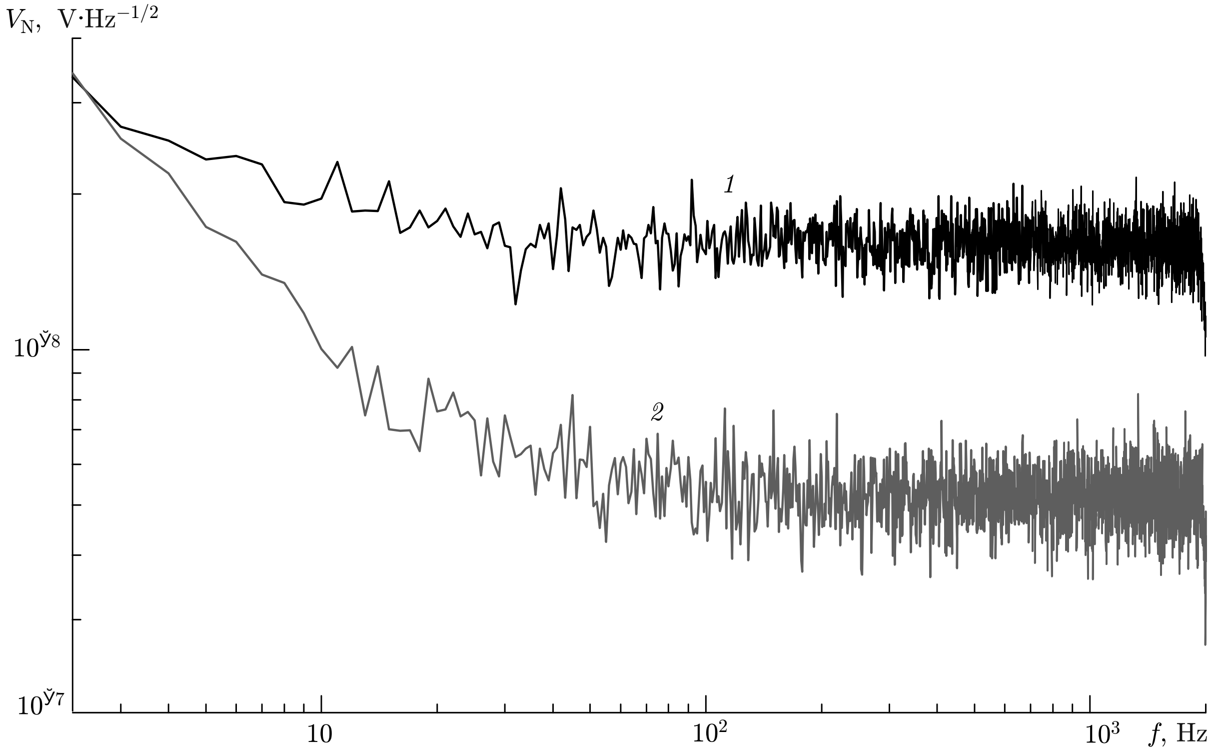

Fig. 3. Noise spectral powers of the microbolometer (*1*) and the amplifier (*2*) at room temperature.

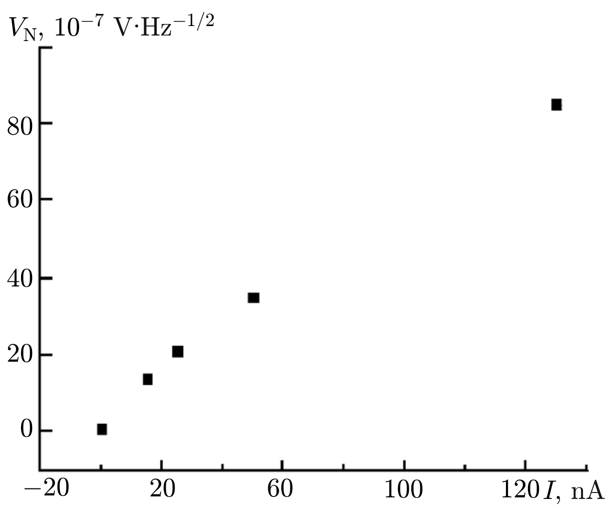

Fig. 4. The noise spectral-power value V_N as a function of the measurement current I.

the working temperature at which its resistance becomes much greater, the role of the noise current of the amplifier becomes more significant and the current noise of the recording cascade can be observed. It should also be noted that conductivity of the Si–Cr_x films is related to the Coulomb-blockade effect [12]. For such a conductivity type, appearance of additional noise proportional to the current and related to overcoming the potential barriers, including the Coulomb repulsion, by the charge carriers is possible, i.e., the shot effect can appear. Note that this issue was not discussed in the literature with respect to constructing bolometers based on such films. Figure 4 shows the amplitude of the noise spectral density as a function of the measurement current. The linear part of this dependence corresponds to the measurement current, which does not heat the sensitive element of the bolometer. Comparing this dependence with the voltage noise, one can find an optimum value of the measurement current, which does not contribute to the noise characteristics of the bolometer.

The noise level was measured for conducting a current of 1nA. For such a current, the Nyquist noise and the recording-electronics noise are predominant. The response to the microwave signal was amplified with the help of a low-noise amplifier and digitized. The fast Fourier transform was used for determining the spectral density of the signal. Figure 5 shows the bolometer optical response to a microwave signal with mechanical modulation at frequencies of 1 and 5 Hz. The noise level was about 50 nV/Hz$^{1/2}$. It is mainly determined by the Johnson noise (about 40 nV/Hz$^{1/2}$) and the recording electronics noise (about 10 nV/Hz$^{1/2}$), which yield an r.m.s. noise value of 42 nV/Hz$^{1/2}$. The time constant of the bolometer

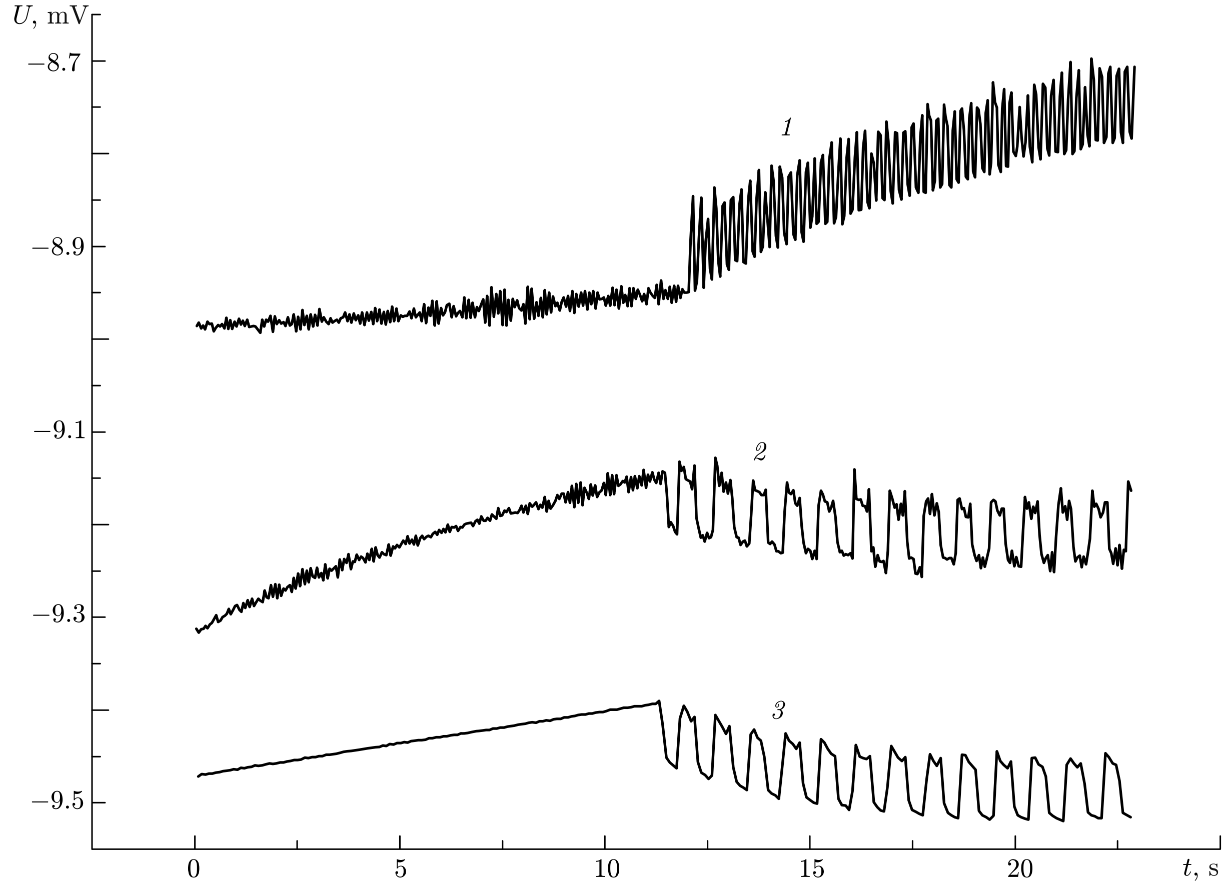

Fig. 5. Optical response of the bolometer to the microwave signal with a frequency of 350 GHz with mechanical modulation. Curve *1* corresponds to the microwave-signal modulation at a frequency of 5 Hz and curves *2* and *3*, to modulation at a frequency of 1 Hz for various experimental realizations. Gradual variation in the microbolometer resistance is due to a slight variation in the temperature of the cold cryostat plate.

response was measured using an oscilloscope and analyzing the signal rise and fall fronts. According to the data obtained from this measurement, the bolometer-time constant turns out to be no less than 10 ms.

To estimate the sensitivity of the manufactured microbolometer model, optical measurements of the bolometer response to the microwave signal were performed. The backward-wave oscillator (BWO) with a radiation frequency of 350 Hz and a power of 5 mW was used as a microwave source. The directional pattern of the BWO output radiation had a width of 30°. The radiation incident on the bolometer was modulated by the mechanical modulator with frequencies of 1–5 Hz. The bolometer resistance amounted to 5–0.5 MΩ in the temperature range 60–70 K, respectively. The temperature coefficient of the cermet-film resistance at such a temperature was about $\alpha = 8.5 \cdot 10^{-2}\,\mathrm{K}^{-1}$. The dependence of the optical response of the bolometer to the microwave signal with a frequency of 350 GHz with mechanical modulation is given in Fig. 5. The value of the voltage (i.e., optical response), which resulted from the microwave-radiation incidence on the bolometer, amounted to $U_{\mathrm{resp}} \approx 0.1$ mV for a measurement current of 1 nA. The dimensions of the sensitive element of the bolometer were about $100 \times 100\,\mu$m. The radiation wavelength at a frequency of 350 GHz equals $850\,\mu$m in free space. If the sensitive-element size is much smaller than the diffraction limit, it can be assumed that the effective bolometer area corresponds to the radiation wavelength and amounts to $S_{\mathrm{bolo}} = 0.8 \times 0.8\,\mathrm{mm}^2$. In the bolometer plane, the size of the microwave-radiation beam is 50×50 mm and assuming that the absorption coefficient is equal to 0.5 (which is typical of the absorber with a surface resistivity of 350 Ω per square), the bolometer-absorbed power is $W_{\mathrm{Inc}} \approx 50$ nW. Therefore, the bolometer volt–watt sensitivity $S = U_{\mathrm{resp}}/W_{\mathrm{Inc}}$ is about $S \approx 5 \cdot 10^3$ V/W. It is noteworthy that we used the linear segment of the current–voltage characteristic (and the linear segment of the dependence of the value of the noise spectral power on the measurement current). Actually, an increase in the measurement current by an order of magnitude should also increase the volt–watt sensitivity by an order of magnitude without increasing the current noise.

Using a certain value of the volt–watt sensitivity S and the measured amplitude of the noise-density level, which is equal to $50\,\mathrm{nV/Hz^{1/2}}$, one can calculate the noise-equivalent power (NEP) for the temperature $T = 60\,\mathrm{K}$: $\mathrm{NEP} = 5\cdot 10^{-11}\,\mathrm{W/Hz^{1/2}}$. It is also possible to calculate the heat-loss coefficient $G = 5\cdot 10^{-7}\,\mathrm{W/K}$ and the spectral density P of thermal noise for the temperature $T = 60$ K: $P = \sqrt{4kT^2G} = 3\cdot 10^{-13}\,\mathrm{W/Hz^{1/2}}$, where k is Boltzmann's constant. When the microbolometer is irradiated by laser radiation with a wavelength of $0.63\,\mu\mathrm{m}$, the experiment yields similar values of S and NEP. Therefore, we can state that a wideband microwave-radiation receiver, which can be of interest for various applications, has been developed.

As has already been mentioned, the electron transport in cermet films at low temperatures is significantly influenced by the Coulomb-blockade effect [12]. In this case, for small thicknesses of such films, the charge-carrier motion is influenced by the surrounding media since the charge shielding depends on the permittivities of the materials located under and above the film. If a thin ferroelectric film with a Curie point of about 70 K, which corresponds to the working temperature of the bolometer, is located near the cermet film, then the microbolometer sensitivity can be increased by an order of magnitude at the temperature of the phase transition of a ferroelectric, when its permittivity abruptly changes [13, 14].

4. CONCLUSIONS

The model of a freely hanging microbolometer on the basis of the Si–Cr_x alloy has been manufactured and the first estimates of its sensitivity have been performed. According to the analysis of the available literature, this material has not been previously used when constructing a microwave microbolometer. Varying the silicon and chromium fractions in a cermet film, one can specify the bolometer working temperature in the range from 4.2 K (and lower) to 70–80 K. The microbolometers manufactured using the developed technology have small capacitance and inductance due to their geometry. On the basis of the cermet Si–Cr_x films, one can develop various-construction bolometers including the uncooled microbolometer having a sensitivity comparable with that already realized for the uncooled microbolometers based on vanadium oxide. To this end, one should increase the cermet-film resistivity and optimize the bolometer geometry.

This work was supported by the U.S. Civilian Research and Development Foundation (project No. FSCX-14-61077-0), the Ministry of Education and Science of the Russian Federation (project No. 3.2054. 2014/K) and the Russian Foundation for Basic Research (project No. 15–47–02552) and also performed within the framework of fulfilling the state assignment to the Institute of Applied Physics of the Russian Academy of Sciences (project No. 0035–2014–0021, topic 12.12 "Devices and methods for microwave radiometry"). We thank N. S. Gusev, S. A. Gusev, A. V. Zenkevih, P. A. Yunin, and O. L. Ermolaeva for assistance in the structure certification and experimentation. During our work, we used the equipment of the Collective Use Center "Physics and Technology of Micro- and Nanostructures."

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