ISSN 1063-7850, Technical Physics Letters, 2018, Vol. 44, No. 7, pp. 581–584. © Pleiades Publishing, Ltd., 2018.
Original Russian Text © A.V. Merenkov, S.V. Shitov, V.I. Chichkov, A.B. Ermakov, T.M. Kim, A.V. Ustinov, 2018, published in Pis'ma v Zhurnal Tekhnicheskoi Fiziki, 2018, Vol. 44, No. 13, pp. 59–67.

A Superconducting Resonator with a Hafnium Microbridge at Temperatures of 50–350 mK

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Received December 11, 2017

Abstract—A high-quality superconducting resonator with a microbridge of hafnium film for use in a circuit for readout a terahertz-band imaging array with frequency division multiplexing is demonstrated experimentally. The variability of the impedance of the bridge at a frequency of 1.5 GHz, which is a key factor in the control of the quality of the resonator, is studied. The bridge, having a thickness of about 50 nm, a critical temperature $T_C \approx 380$ mK, and a plan size of 2.5 × 2.5 μm, was connected as a load of a resonator made of niobium film with a thickness of about 100 nm ($T_C \sim 9$ K). It is shown that the bridge smoothly changes its impedance proportionally to the bias power in the entire temperature range. The effective thermal insulation of the bridge was measured in a dilution cryostat at temperatures of 50–300 mK. Thermal conductivity G of the bridge was calculated and found to be $\sim 4 \times 10^{-13}$ W/K, which gives an estimate of the sensitivity of the structure in the bolometric mode NEP $\approx 8 \times 10^{-19}$ W/Hz$^{1/2}$ at a temperature of 150 mK.

DOI: 10.1134/S106378501807012X

Fundamental research in radio imaging, including radio astronomy, requires the use of ultrasensitive detectors containing more than 1000 pixels. To read cooled arrays, methods of frequency division multiplexing (FDM) making it possible to receive information from different pixels by one common cable have been developed. This reduces the thermal load and allows the maximum use of the integration time of each pixel [1]. There are two competing types of detectors: nonequilibrium kinetic inductance detectors (MKIDs) [2] and bolometric sensors in which the heating of the absorber is measured by an equilibrium transition-edge sensor (TES) [3, 4]. An important advantage of an MKID is the integrated circuit for readout at frequencies on the order of 1 GHz with a single semiconductor amplifier of the standard of 50 Ω. In this respect, a TES is inferior, because it requires an expensive SQUID amplifier operating at frequencies below 1 MHz, which makes it difficult to create an integrated readout circuit. At temperatures below 1 K, the electron subsystem of many materials interacts with the crystal lattice weakly and can be heated relatively independently, especially near the superconducting transition [5]. The advent of nonequilibrium nano-HEB detectors (HEB stands for "hot-electron bolometer") [6, 7], which can be conditionally classified as self-heating TESs, prompted us to develop the concept of radio-frequency transition-edge sensors (RFTESs) [8–10]. We proposed to measure such heating at resonator frequencies of a few gigahertz, supposing that it is possible to realize a variable impedance of the bridge at relatively high frequencies. We succeeded in demonstrating experimentally an electrodynamic prototype with a probing frequency of ~5 GHz at temperatures of 1.5–4.5 K with a noise-equivalent-power (NEP) optical sensitivity of about 10^{-14} W/Hz$^{1/2}$ [9]. The aim of this work is to demonstrate the variability of the impedance of the bridge at lower temperatures and low gap energy in the transition region, which is a critical parameter in the application of our frequency multiplexing method for bolometric matrices with a sensitivity better than 10^{-18} W/Hz$^{1/2}$.

The equivalent circuit and a photograph of the new chip are shown in Fig. 1. A quarterwave resonator folded for compactness plays simultaneously the role of a narrow-band filter (~0.1 MHz) and an impedance transformer of the line connected to it at a frequency of 1.5 GHz. Quality factor $Q \approx 10000$ was implemented in an integrated circuit with the following parameters: bolometer resistance $R_B = 10\ \Omega$ and equivalent capacitances $C_1/C_2 = 100$ and $C_1 + C_2 \approx C_R$. A variation in the state of the bridge changes the current in the resonator. The connection to a line of 50 Ω

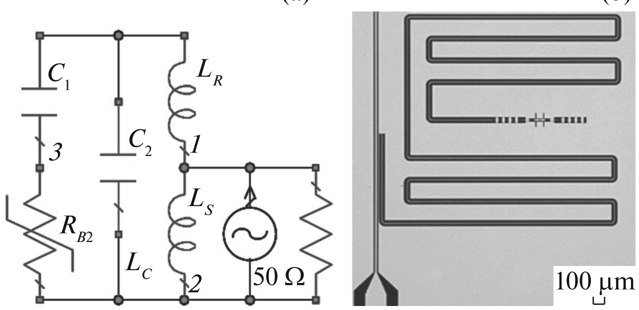

Fig. 1. (a) Equivalent circuit of an RFTES with a frequency selection circuit. (*1*, *2*) The input and output ports of the chip and (*3*) the port for connecting the bridge. (b) RFTES detector in a resonator matched according to the 50 Ω standard. Gray color corresponds to metal; black color, to the substrate.

creates the required embedding impedance $R_{SH} \ll R_B$, as required by the stability condition of a classical TES [11]. In contrast to the MKID mode, the current at 1.5 GHz is considered invasive; i.e., it heats the bridge and creates conditions for shifting the temperature of its electron subsystem to the transition from the superconducting to normal (self-heating) stage. The terahertz signal, the effect of which was studied in [6, 7] and which is not directly discussed in this paper, can come from an antenna integrated with a resonator by analogy with an MKID (Fig. 1b) in the form of photons with an energy much higher than the gap energy of the material of the bridge. For such photon energies, the bridge behaves like a normal metal and variability of its impedance is certainly absent, but an additional heating of the electron subsystem takes place, which can be detected at a direct bias current [6]. If the frequency of this bias is not too high, then the variation in bridge impedance $Z(T, f)$ should lead to a variation in quality factor Q of the resonator and variation in transmission coefficient S_{21} of the line connected to it (similarly to an MKID).

There are several theories suitable for describing the variations in the impedance $Z(T, f)$ of a superconductor at frequencies that cannot be considered low [12–14]. They all predict that, with increasing frequency, ratio $dZ(T, f)/dT$, which describes the variability of the complex impedance, decreases, with its active component being manifested at temperatures well below the critical temperature of the bridge material. In practice, dependence $R(T)$ of the resistance of the film is never as sharp as predicted by the theory. This enables us to propose the hypothesis that there exists frequency f_0 at which the theoretical steepness is comparable with experimental and the high-frequency effect can be neglected. The Mattis–Bardeen theory in the Pippard limit makes it possible to calculate normalized resistance $R(T, \omega)$ of a microbridge from hafnium with critical temperature $T_C \approx 0.36$–0.4 K, using the following equations from [13]:

$$\frac{R}{R_N} = \frac{\sigma_1\sigma_N}{\sigma_1^2 + \sigma_2^2},$$

where

$$\frac{\sigma_1}{\sigma_N} = \frac{2}{\hbar\omega}\int_{\Delta(T)}^{\infty}(f(u) - f(u+\hbar\omega))g(u)du + \frac{1}{\hbar\omega}\int_{\Delta(T)-\hbar\omega}^{-\Delta(T)}(1 - 2f(u+\hbar\omega))g(u)du,$$

$$\frac{\sigma_2}{\sigma_N} = \frac{1}{\hbar\omega} \times \int_{\Delta(T)-\hbar\omega,-\Delta(T)}^{\Delta(T)} \frac{(1-2f(u+\hbar\omega))(u^2 + \Delta(T)^2 + \hbar\omega u)du}{\sqrt{\Delta(T)^2 - u^2}\sqrt{((u+\hbar\omega)^2 - \Delta(T)^2)}},$$

and $f(u)$ is the Fermi–Dirac function and function $g(u)$ is given by the formula

$$g(u) = \frac{u^2 + \Delta(T)^2 + \hbar\omega u}{\sqrt{u^2 - \Delta(T)^2}\sqrt{(u+\hbar\omega)^2 - \Delta(T)^2}}.$$

A comparison of the calculation results with the measured dependence $R(T)$ for our hafnium films is shown in Fig. 2a and shows their not overly large difference at a frequency of 1.5 GHz. The full-wave simulation of the samples was carried out using the NI AWRDE Microwave Office software package. All the elements of the structure were made of a niobium film with a thickness of ~100 nm ($T_C \approx 9$ K), while the bridge was made of a hafnium film with a thickness of ~50 nm (Figs. 1b, 2b). The chips were manufactured in the Superconducting Metamaterials laboratory of the National University of Science and Technology MISiS (NUST MISiS) on single-crystal silicon substrates. Mask-free exposure of the photoresist using a Heidelberg μPG501 scanning-laser lithograph was used. Niobium and hafnium films were deposited by DC magnetron sputtering at a chamber's base pressure of (8–9) $\times 10^{-8}$ mbar and an argon pressure of 5×10^{-3} mbar. The deposition rate was 22 nm/min for niobium and 28 nm/min for hafnium. The purity of the target materials was 99.99%. The hafnium bridge was formed by lift-off photolithography process. The S-parameters were measured with an Agilent vector microwave-network analyzer in the range of chip input power from –110 to –80 dBm (10^{-15}–10^{-12} W at the bridge itself). For the structure shown in Fig. 1b, the resonance frequency was 1.5001 GHz, which practically coincided with the design value. Transmission coefficient S_{21} was measured at a fixed power in the temperature range of 50–350 mK, and, at a fixed temperature from this range, the bias power was varied. Judging from the dependences of S_{21} obtained, with variations in the power and temperature, the imped-

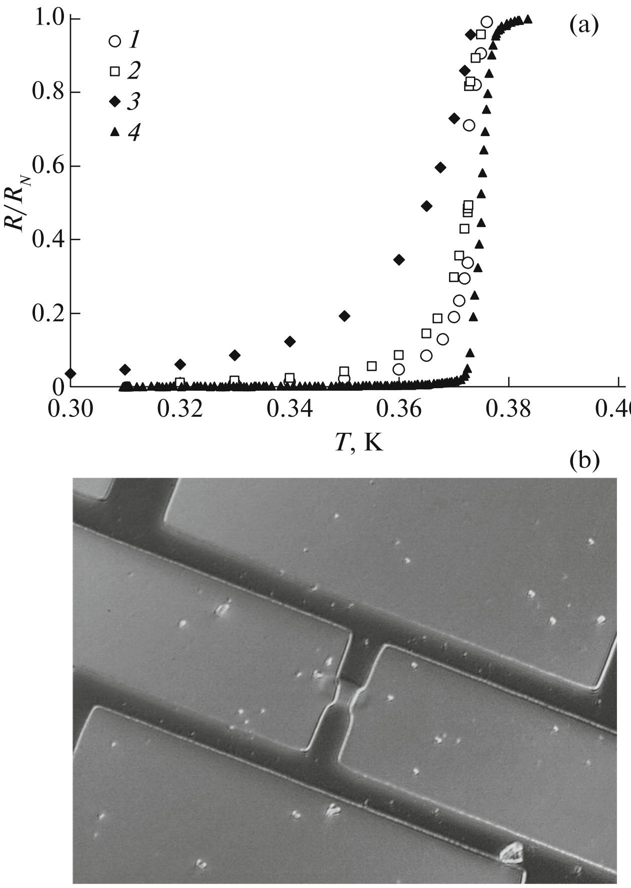

Fig. 2. (a) The real (active) part of the normalized high-frequency impedance of a hafnium bridge at frequencies of (*1*) 1, (*2*) 1.5, and (*3*) 5 GHz in comparison with (*4*) direct-current measured ratio $R/R_N(T)$. (b) Photograph of a hafnium microbridge embedded in a quarterwave resonator.

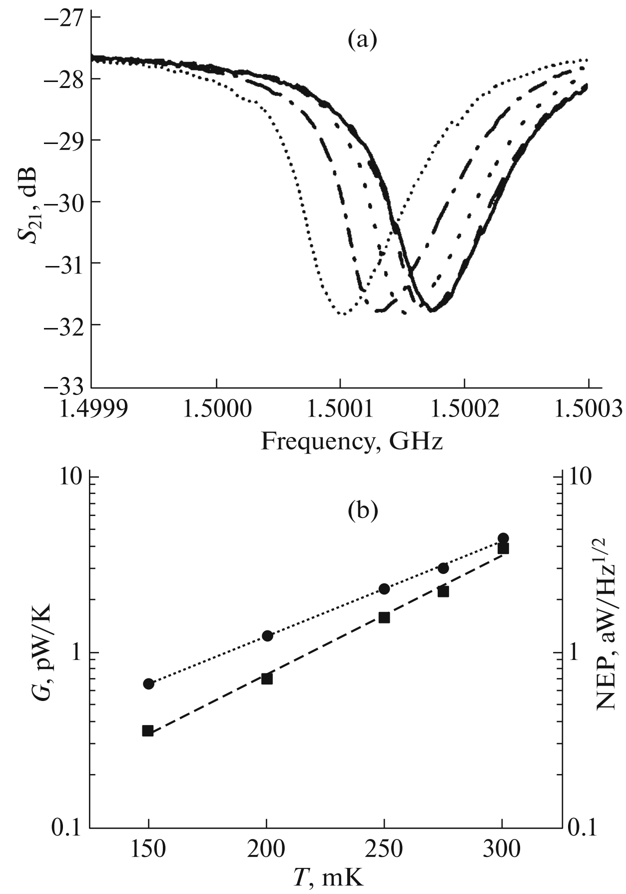

Fig. 3. (a) Steady microwave heating of the bridge (constant quality of the resonator): the decrease in temperature (from right to left, 275, 250, 200, 150, and 100 mK) is compensated by a bias power (–43.9, –42.5, –41.4, –41, –41 dBm, respectively). The output power of the analyzer is given as measured neglecting the 40-dB attenuation by cooled attenuators and ~9-dB attenuation in the connecting cables. (b) (Squares) Thermal conductivity G of the bridge calculated from the experimental data given in (a) and (circles) the corresponding sensitivity upon pumping at a resonator frequency of 1.5 GHz.

ance of the bridge varies smoothly, with impedance jumps, hysteresis, and other manifestations of instability observed in [8, 9] being absent. The result of the experiment on steady value of S_{21} (a constant temperature of the electron subsystem of the bridge) at different cryostat temperatures T_i by selecting bias power P_i is shown in Fig. 3a. It is known that, with decreasing temperature, thermal conductivity of the electron subsystem of hafnium $G(T)$ decreases by a power-law proportionally to $\sim T^N$, where $N = 3–5$ [5]. The condition of constant heating obtained in the experiment can be written in the form of an equation for the replacement of the heat outflow by a bias power, $G_i(T_i - T_{i+1}) = P_{i+1} - P_i$, the solution of which for a set of experimental points is shown in Fig. 3b. This dependence can be approximated as $G(T) \sim T^3$, which indicates the heating of the electron subsystem of the bridge [5, 15]. The theoretical limit of the NEP sensitivity corresponding to experimental thermal conductivity $G \approx 4 \times 10^{-13}$ W/K can be calculated by the classical formula $\mathrm{NEP} = \sqrt{4k_B T^2 G}$, which is also shown in Fig. 3b. In conclusion, it should be noted that thermal conductivity G can be reduced by at least an order of magnitude due to a reduction in the volume of the bridge by turning to submicron lithography. The record estimate NEP = 8×10^{-19} W/Hz$^{1/2}$, obtained on the basis of the experimental data at a temperature of 150 mK, will be refined in the near future in an optical experiment using a vacuum blackbody radiation source [16]. Thus, our studies have demonstrated the variability of the impedance of a superconducting hafnium film due to the heating of its electron subsystem. Based on the method of steady heating of electron gas, the thermal conductivity of the bolometer has been measured and the possibility of creating a new ultrasensitive detector for terahertz FDM arrays has been confirmed.

Acknowledgments. This work was supported, in the part of theoretical calculations and simulation, by the Ministry of Education and Science of the Russian Federation within the Program for Improving the Competitiveness of the National University of Science and Technology MISiS (grant no. K2-2014-025) and, in the part of experimental research, by the Russian Science Foundation (grant no. 17-19-01786).

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Translated by E. Chernokozhin