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Experimental study of a SINIS detector response time at 350 GHz signal frequency

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Abstract. Response time constant of a SINIS bolometer integrated in an annular ring antenna was measured at a bath temperature of 100 mK. Samples comprising superconducting aluminium electrodes and normal-metal Al/Fe strip connected to electrodes via tunnel junctions were fabricated on oxidized Si substrate using shadow evaporation. The bolometer was illuminated by a fast black-body radiation source through a band-pass filter centered at 350 GHz with a passband of 7 GHz. Radiation source is a thin NiCr film on sapphire substrate. For rectangular 10÷100 μs current pulse the radiation front edge was rather sharp due to low thermal capacitance of NiCr film and low thermal conductivity of substrate at temperatures in the range 1-4 K. The rise time of the response was ~1-10 μs. This time presumably is limited by technical reasons: high dynamic resistance of series array of bolometers and capacitance of a long twisted pair wiring from SINIS bolometer to a room-temperature amplifier.

1. Introduction

Planar bolometers with Superconductor-Insulator-Normal metal-Insulator-Superconductor (SINIS) tunnel junctions due to tiny volume of normal metal absorber below 0.1 μm^3 and low thermal capacity about 10^{-17}-10^{-18} J/K at temperatures 0.1-0.2 K are expected to have a very short response time. Time constant for the input signal of about 10-100 ns is determined by thermalization of electron system due to electron-electron interactions [1, 2]. Potentially, the small time constant of the SINIS bolometers is advantageous compared to the well-established superconducting Transition Edge Sensors (TES) with time constant over millisecond [3]. In a previous study, the relaxation process in SINIS thermometer with absorber volume of 4.5 μm^3 for heating or cooling by a current pulse at a bath temperature of 270 mK was measured to be 1.2 μs [4]. A contradicting result for NIS thermometer measurements in the megahertz band with response time of 100 ms was obtained in [5]. There are no direct measurements of response time for SINIS bolometers illuminated with terahertz radiation. This is important for estimating the performance of RF readout and frequency multiplexing of multi-pixel systems.

2. Measurement setup

In our experiments, we use a thermal radiation source placed inside the cryostat close to the bolometer. This source comprises of a sapphire substrate and a NiCr resistive radiating film, and is mounted on thin wires providing bias current as well as heat sinking to the cold plate at 0.4 K. DC current can provide overheating by few Kelvin for applied power of the order of 10 μW. Temperature of the black body is monitored by a RuO_2 surface-mount resistor glued to the substrate. According to estimations in [6] the time constant of RuO_2 thermometer is about 100-200 μs. Radiation from this black body source is guided through an aperture 7 mm in diameter covered with a band-pass filter as in [1, 2], and focused by an extended hyper-hemisphere sapphire lens which is attached to the back side of the substrate with the bolometer.

In first series of experiments we study a series array of 25 annular ring antennas 307 μm in diameter each with two bolometers [7], see Fig. 1. Such antenna consists of two half-rings made of thick gold and connected with SINIS bolometers. Antennas are arranged in 5 rows with 5 elements each, covering an area of 3x3 mm^2, and connected in series for measurements of voltage response. Absorbers are formed of a Fe/Al bilayer strip with dimensions of 1x0.1x0.021 μm^3. The bilayer was formed by depositing 0.7 nm Fe followed by 14 nm of Al. This ensures that the Al is non-superconducting at experimental bath temperatures. The total volume of the absorber also includes the volume of the normal metal film under the two tunnel junctions with area of 0.4x1.8 μm^2 making the total volume of the normal metal electrode 0.03 μm^3 for one bolometer. The whole structure with the ring inductance and NIS junction capacitances is designed for central frequency of 350 GHz. For simple estimations of absorbed thermal radiation one can assume this structure as a single-mode receiver as in [1, 2]. Experimental results are presented for bath temperatures 90-100 mK.

In a second series of experiments, we studied SINIS bolometers with large area NIS junctions and a suspended Cu absorber integrated in a log-periodic antennas. In case of a suspended absorber, the heat link to the substrate is significantly reduced making thermalization of the electron system more effective.

3 Experimental results

For evaluation of the receiver performance, we first measured Current-Voltage characteristics (IV curves) at dc bias for different levels of irradiation from the source. For radiation source temperatures of 0.5 K, 5.8 K, 8.1 K, 11 K, and 14 K, we present IV curves in Fig. 2 (left panel), and voltage response in the right panel with corresponding numbers of the loaded curve. The "loaded" IV curves (curves 2-5) are subtracted from an unloaded IV curve (curve 1) to calculate the receiver response. The voltage response is the difference in response voltage as a function of bias current. We estimate the additional incoming power for one ring antenna as 1.5 pW, 3.5 pW, 6.5 pW, and 10 pW for curves 2, 3, 4, 5. It should be mentioned that an aperture of 7 mm reduces the actual incident power by a factor over 4. Taking into account the source temperature and geometry of experiment we can estimate voltage response on the absorbed power. Dynamic resistance of bolometer array at the response maximum is in the range of 1÷10 MΩ, a twisted pair wiring capacitance is 80-100 pF, the time constant of such RC circuit is 10-100 μs, that is too high. For pulse measurements, we choose the dc bias for which dynamic resistance of SINIS is in the range of 10÷100 kΩ, the response level is several times less compared to the maximum, and time constant of wiring is reduced down to 1 μs.

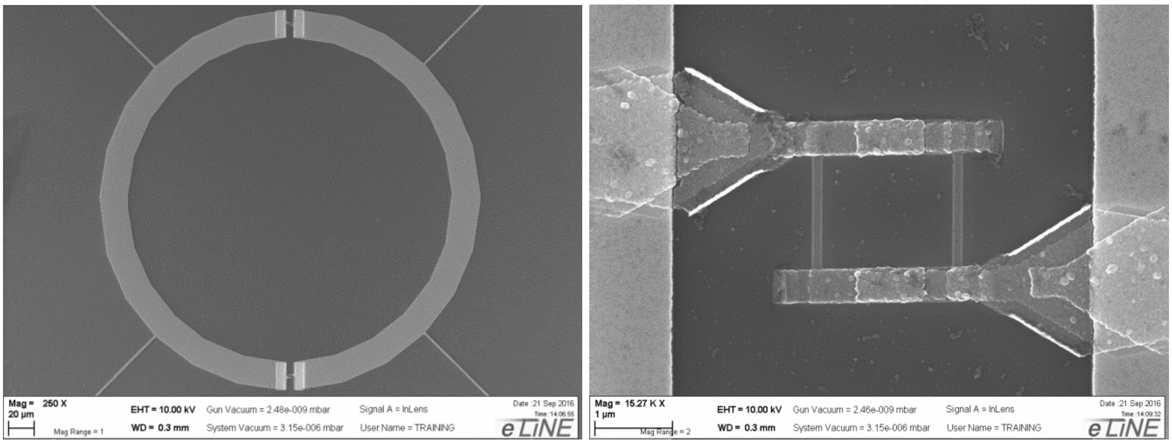

Figure 1. SEM view of single annular ring antenna (left panel) with two identical SINIS bolometers (right panel).

To study the thermodynamics of the bolometer, we irradiate the device with a heating pulse of relatively large power and very short rise time. In our case, the sapphire substrate with an area of 2 cm^2 and 0.3 mm thickness, the thermal capacity can be calculated as 29*T^3 nJ/K. Thermal capacity of metal films less than 0.1 μm thick can be neglected. When applying an electric pulse with power of 1 W with duration of 1 μs, the source is heated up to 5 K and then preserves this temperature for a few hundred milliseconds. Source cooling back to bath temperature time can approach a second due to a very low thermal sink through bias and suspension wires.

Under experimental conditions, the black body source was heated by current pulse with an instant power of 0.4 W or less and corresponding energy below 4 μJ for 10 μs pulse duration. Current pulse was fed to black body through a symmetric line to reduce a crosstalk to amplifier input. The bolometer output voltage was preamplified and fed to an input of a 2-channel TEKTRONIX® TDS 1012B oscilloscope operated in a waiting mode. Synchronizing pulses were applied to the second input of the oscilloscope. For reducing pulse interferences that can be up to 1 μV measurements were done in the bolometer bias reversal mode +Vbias / -Vbias. When subtracting responses at positive and negative bias voltages we obtain response to radiation, and if summing up we get interference component and estimate of how much it can affect our measurements. For increasing the signal to noise ratio, we integrate many cycles keeping period in between that is enough to cool down the radiation source. Control over process was using a special program developed within LabView environment.

When NiCr film is heated by a current pulse, its temperature determines the instant radiation power. For maximum heating pulse power of 0.2 W/cm^2 the temperature gradient across the 15 nm thick film does not exceed 0.1 mK. Kapitza temperature drop between film and sapphire at T=4 K is below 0.1 K and decreases as T^{-3}. For this estimation we use Kapitza resistance for indium-sapphire interface from [8] that is higher compared to NiCr-sapphire case. Temperature variation in sapphire with its thermal conductivity about 100 W/(m*K) [9] is about 6 mK. So we assume that during current pulse, the temperature of radiating film is the same for the whole radiation source. Time constant of the source can be estimated from the following considerations. It operates at temperature up to 5 K, its thermal capacitance is C=2.9*10^{-8}T^3 J/K [9], thermal conductivity is proportional to G~T^3 [10] that makes at T=5 K the time constant τ=C/G=20÷30 ns. This time is much less compared to bolometer together with readout time constant that is of the order of a microsecond.

Figure 3 shows the measurement results for heating pulse of 20 V during 10 μs to the radiation source with resistance of 900 Ω. Taking into account the response level at dc heating we can estimate the radiation source temperature as T_{rad}=4±0.2 K. Taking into account heat capacitance of sapphire and applied energy, estimation of black body source temperature brings T_{rad}=4.5±0.3 K.

For longer heating time of black body source about 100 μs the dependence is more complicated, see Fig. 4. In the initial part of dependence after heater switch-off the fitting corresponds to time constant of 16 μs, after that dependence approaching exponent with time constant of 120 μs. Such increase can be a manifestation that not only normal metal but also superconductor and silicon substrate are overheated.

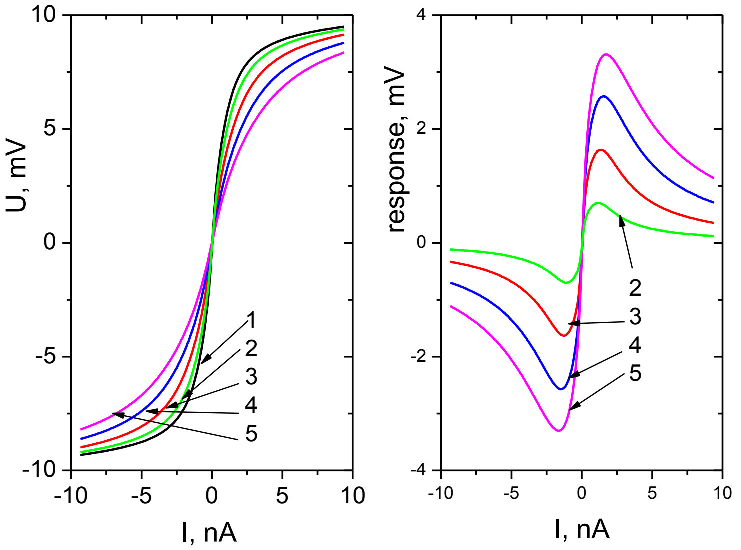

Figure 2. IV curves (left panel) and voltage response (right panel) for series array of 25 annular ring antennas with SINIS bolometers.

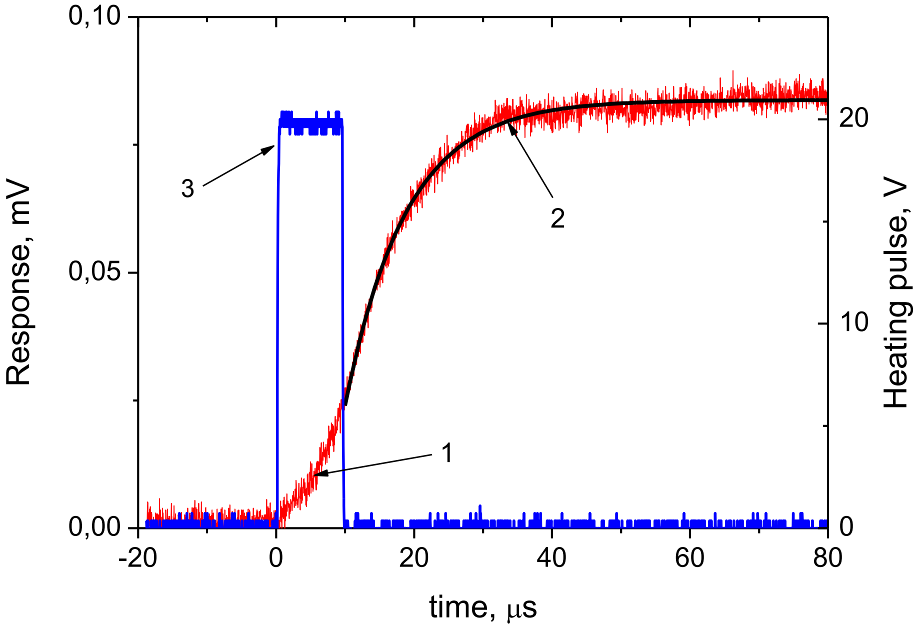

Figure 3. Voltage response of series array SINIS bolometer with dc bias ±7 nA for black body radiation source heated by rectangular shape pulse 20 V amplitude during 10 μs. Curve (1) is time dependence of response averaged for 128 cycles, (2) exponent that fitting dependence (1) after the end of warming pulse. Time constant of this exponent is 8.8 μs. Curve (3) initial heating pulse. Radiation power referred to one antenna with response of 85 μV is estimated to be about 0.5 pW.

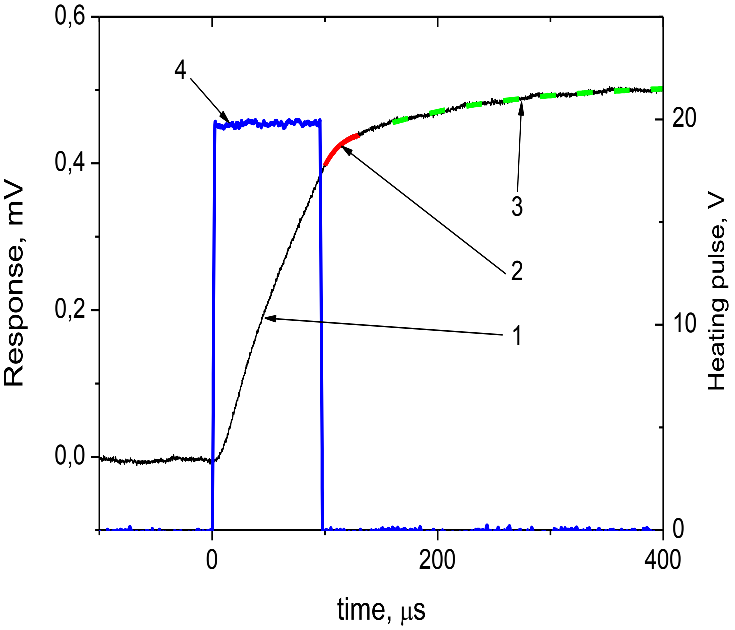

Fig. 4.. Voltage response of a SINIS array for pulse heating of radiation source with amplitude of 20 V and duration of 100 μs. Curve (1) is time dependence of bolometer response averaged for 128 pulses, (2) exponent fitting just after the end of heating pulse , with time constant of τ=16 μs, (3) exponent fitting after 50 μs from the end of current pulse, with time constant τ=120 μs, (4) the heating pulse.

We also measured the same dependence for SINIS bolometer with a suspended absorber and larger NIS junctions [11]. Bolometer is integrated in a log-periodic antenna. Level of signal was less because of just a single bolometer under test contrary to 25 bolometers in previous part, and dynamic resistance is 14 kΩ instead of 100 kΩ. Results are presented in Fig. 5. Time constant in this case decrease down to 2.3 μs.

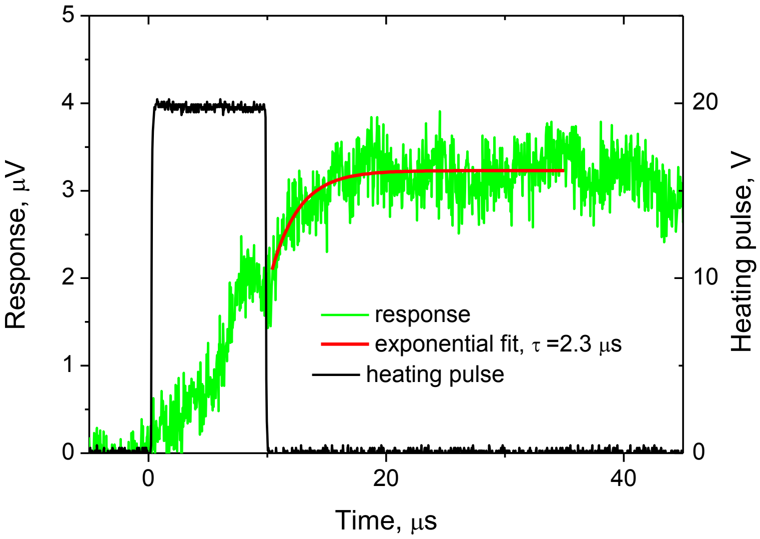

Figure 5 Response of bolometer with a suspended absorber to the radiation by heating pulse 20 V*10 μs. Response reaches exponentially the permanent value with τ = 2.3 μs.,

4. Conclusion

An important issue for SINIS bolometer applications is a proper estimation of its time constant for variations in the incoming Terahertz signal. According to our measurements for series array of SINIS bolometers at 100 mK bath temperature, the time constant is below 10 μs for short pulses and increase to 100 μs for a longer irradiation accompanied with heating of the wiring and substrate. For a low-resistance SINIS bolometer with suspended absorber, the measured time constant is below 1 μs. In our measurements resolution is limited by τ=RC and can be substantially reduced by using parallel array of bolometers to reduce the resistance R and measurements with cold amplifier to avoid parasitic capacitance C of wiring. For higher bath temperatures, the time constant is reduced dramatically [4]. If, at 100 mK, the time constant it is over 10 μs, then at 300 mK it is 1 μs, and at 500 mK it is estimated to be 0.1 μs. In the case of the SINIS bolometer with strong electro-thermal feedback, known as Cold Electron Bolometer (CEB), the time constant can be reduced when bolometer is biased close to the energy gap and demonstrates electron cooling. According to [12] the intrinsic time constant of CEB can vary from 10 to 70 ns for signal power up to 1 pW. Such time constant is much shorter compared to Transition Edge Sensor (TES) for which it is in the range of milliseconds.

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