Terahertz Transition-Edge Sensor with a Kinetic-Inductance Amplifier at 4.2 K.

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***Abstract*— Different terrestrial terahertz applications would benefit from large-format arrays, operating in compact and inexpensive cryocoolers at 4.2 K with sensitivity, limited by the 300-K background radiation only. A voltage-biased Transition-Edge Sensor (TES) as a THz detector can have sufficient sensitivity and has a number of advantages important for real applications, however it requires a low-noise current readout. Usually, a current amplifier based on Superconducting Quantum-Interference Device (SQUID) is used for readout, but the scalability of this approach is limited due to complexity of the operation and fabrication. Recently, it has been shown that instead of SQUID it is possible to use a current sensor, which is based on the nonlinearity of the kinetic inductance of a current-carrying superconducting stripe. Here, we demonstrate the operation of a voltage-biased TES with a microwave kinetic-inductance current amplifier at temperature 4.2 K. We measured the expected intrinsic Noise-Equivalent Power NEP ~ 5×10^{-14} W/Hz$^{1/2}$ and confirmed that a sufficient sensitivity of the readout can be reached in conjunction with a real TES operation. The construction of an array with the improved sensitivity ~ 10^{-15} W/Hz$^{1/2}$ at 4.2 K could be realized using a combination of the new current amplifier and already existing TES detectors with improved thermal isolation.**

I. Introduction

Large-format arrays of sensitive THz detectors are required today in different terrestrial applications. Among them is THz passive security scanning for concealed hazardous objects, THz imaging for non-destructive testing (NDT) in production lines and imaging far-infrared Fourier-Transform Spectroscopy for material research and atmospheric studies [1-5]. Estimations show that the sensitivity of a diffraction-limited single-pixel THz detector with Noise Equivalent Power NEP ~ 10^{-15} W/Hz$^{1/2}$ would be sufficient for applications with a 300-K background [6].

Cryogenic detectors can achieve the required sensitivity, but construction of large arrays is challenging. A practicable system should operate at temperatures not much lower than 4.2 K. A superconducting Transition-Edge Sensor (TES), together with a low-noise current amplifier can have sufficient sensitivity at moderate temperatures [7]. Usually, a Superconducting Quantum Interference Device (SQUID-amplifier) is used for measurements of the current response of a TES. However, readout with many SQUID amplifiers becomes expensive and difficult in fabrication and operation.

A microwave kinetic-inductance detector (MKID) is an example of a scalable detector, which can be operated in the THz spectral range. It is based on high-Q superconducting resonators and a Frequency-Division Multiplexing (FDM) in GHz-range [8]. However, for a pair-breaking process to be effective in the lower THz range, the superconducting energy gap should be small. At 4.2 K this will lead to a low Q factor of the resonator and high generation-recombination noise and thus high NEP.

Luomahaara *et al.* demonstrated a kinetic-inductance magnetometer, which is based on the nonlinearity of kinetic inductance of a small NbN stripe, imbedded in a high-Q resonator [9]. Kher *et al.* demonstrated a current amplifier based on the same principle with a sensitivity ~5 pA/Hz$^{1/2}$ [10].

Here, we demonstrate an operation of a voltage-biased THz TES detector together with an array-scalable current amplifier based on nonlinear-kinetic inductance at 4.2 K. The TES is an antenna-coupled superconducting nano-bolometer, and the current-sensitive inductor is a superconducting nanowire embedded in a high-Q microwave resonant circuit. The resonator is inductively coupled to a coplanar-waveguide transmission line (CPW). It allows for simultaneous injection of the TES current and measurement of the CPW transmission. We called this device a Microwave Kinetic-Inductance Nanowire Galvanometer (MKING). Previously, the MKING achieved a current sensitivity of about 10 pA/Hz$^{1/2}$ [11], which should be sufficient to reach a NEP ~ 10^{-15} W/Hz$^{1/2}$ with a well thermally-isolated THz TES at 4.2 K. This opens a way for building large and sensitive imaging arrays in a compact and inexpensive cryogenic system.

II. Detector System at 4.2 K

A detector system for demonstration of functionality consists of a single TES and a kinetic-inductance current amplifier (MKING) in separate housings. We performed measurements in a liquid-helium-bath cryostat with a THz-transparent window (Fig. 1).

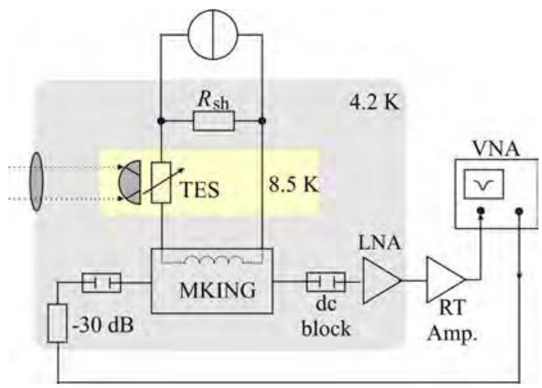

Fig. 1. The schematics of the experimental setup. The gray area is the cold stage of the 4.2 K-cryostat with THz-transparent window; the yellow area is the detector block with antenna-coupled TES on a lens at 8.5 K.

The voltage bias of the TES is realized using a 2-Ω Manganin shunt resistor R_{sh}, which is biased with a current from a room-temperature source. The current inputs of MKING are connected in series with TES. Changes of the microwave transmission of CPW in the MKING are measured using a Vector Network Analyzer (VNA) and a cryogenic microwave low-noise high-electron-mobility transistor (HEMT) amplifier. The equivalent noise temperature Tn of the complete setup is about 25 K and is dominated by the VNA.

A. Transition-Edge Sensor

We have fabricated the THz TES which is an antenna-coupled superconducting nano-bolometer from 5-nm-thin NbN film on a substrate from highly-resistive silicon. The antenna is a bi-layer structure of in-situ magnetron sputtered 20-nm NbN buffer and 200-nm gold layers. The size of the nano-bolometer: length × width = 200 nm × 700 nm. Fig. 2 shows the dependence of the resistance of a nano-bolometer on temperature (R-T curve). The superconducting transitions is at $T_c \approx 9.4$ K. The steepness parameter of R-T curve $\alpha = d(\log R)/d(\log T) \approx 40$. We also measured a non-hysteretic current-voltage characteristic (I-V curve) at 8.5 K, where electrical bias can provide a stable and uniform Joule heating of the nano-bolometer close to T_{c2} (inset in Fig. 2). The estimated thermal conductance of the nano-bolometer $G_{th} \approx 25$ nW/K and a loop gain for the negative electro-thermal feedback $L = \alpha I V_b / G_{th} T \approx 4$ for a working point $V_b = 1$ mV and $T = 9.4$ K. Using these values, we calculated the current responsivity $\Re_I = (L/L+1)/V_b \approx$ 800 A/W, a minimum phonon-limited $\mathrm{NEP_{ph}} = \sqrt{4kT^2 G_{th}} \approx 10^{-14}$ W/Hz$^{1/2}$, and a minimum noise current $\delta I \approx 8$ pA/Hz$^{1/2}$ of the nano-bolometer. The TES chip with the size of 3 mm × 3 mm was glued in the focus of the hyper-hemispherical silicon lens with 12-mm diameter and without anti-reflection coating. The lens with the chip were mounted in a copper block. The temperature sensor and a heater were integrated into a detector block for the control of the TES operation temperature.

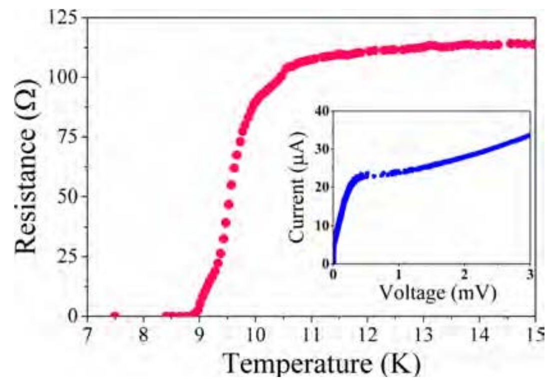

Fig. 2. The R-T curve of the nano-bolometer. Inset: the I-V curve of the nano-bolometer measured at $T = 8.5$ K in a current-bias mode.

B. Kinetic-Inductance current amplifier

To avoid in the future a limited scalability and complexity of readout based on SQUID-amplifier, we replaced it with a superconducting current amplifier, MKING [11]. The resonance frequency of the device is about. The resonance frequency of the device is about 4.7 GHz. In our experiment we used phase response of the device with a fixed frequency of the microwave probe. The single chip of MKING device with a size of 3 mm × 3 mm was mounted into a separeate block with an adapter plate, two SMA connectors for CPW feed line and a DC input port. The particular MKING device had a noise current of about 40 pA/Hz$^{1/2}$ (Fig. 3), which is higher than the value that was demonstrated with the previous 3.8-GHz device.

III. MEASUREMENTS OF RESPONSIVITY AND NEP

To measure the optical response, we applied a THz signal from a calibrated 0.65-THz quasi-optical source through the cryostat window. The measured optical responsivity of 3.3 A/W is much lower than the electrical one due to the low coupling efficiency $\eta = 0.5\%$, since we have a not optimized matching of Gaussian beams from the THz source and TES antenna. Moreover, antenna was not designed for frequencies below 1 THz and its performance at 0.65 THz might be low. For measurement of a small-signal response, we applied a chopped THz signal, which corresponds to an absorbed power of $P_{abs} = 160$ pW (inset in Fig. 4).

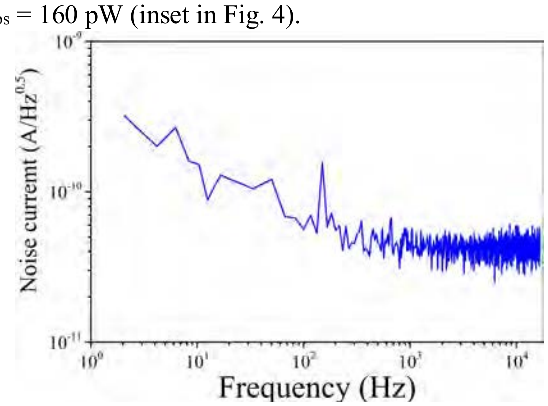

Fig. 3. Measured noise spectrum of the MKING device.

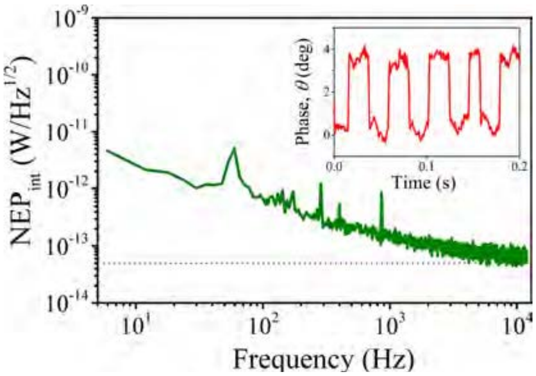

Fig. 4. Measured intrinsic NEP of the detector system. The phase response of the TES-MKING to 160 pW of absorbed THz power (in the inset).

The intrinsic phase-watt responsivity of 2×10^{10} deg/W was obtained in this measurement. To determine intrinsic NEP, we recorded a time trace of the phase without THz signal and plotted spectrum of the phase noise, divided by the measured responsivity (Fig. 4).

C. Discussion

The measured intrinsic NEP reaches 5×10^{-14} W/Hz$^{1/2}$ at white noise level, which is a factor 5 higher than the estimated value. It is probably due to the prevalence of the noise current of the particular MKING over noise of the TES. Indeed, if we take the separately measured TES responsivity and the noise current of the MKING we end up with the same NEP. A reduction of the effective noise temperature of the microwave readout could be achieved using back-end electronics with ADC of higher resolution. This would result in a factor 2 lower noise current of the MKING. Additionally, using the previous version of MKING with lower critical current [11] it would be possible to reach a factor 4 lower NEP.

In order to obtain system NEP ~ 10^{-15} W/Hz$^{1/2}$, which is required for the 300-K background-limited operation, the performance of TES should be improved. A lower system NEP at 4.2 K could be achieved with improved thermal isolation of the bolometer. For a TES on a SiN_x membrane the required thermal isolation has been already demonstrated [12]. A matching of the TES current to the operation range of a MKING with a critical current $I_c \approx 30$ μA seems feasible with the current responsivity $>10^4$ A/W and thus with the noise current $\delta I \approx 10$ pA/Hz$^{1/2}$. Alternatively, antenna-coupled suspended superconducting nano-bolometers can be used, which already demonstrated the required sensitivity [7]. In this case, large membranes are not required and fabrication process is less complex. Both, quasi-optical lens coupling and waveguide coupling, could be used for this type of TES.

Conclusions

The detector system for demonstration of functionality with voltage-biased antenna-coupled TES and kinetic-inductance current amplifier at temperature 4.2 K reached internal NEP ~ 5×10^{-14} W/Hz$^{1/2}$, which is close to the estimated phonon-limited NEP of the particular TES. The sensitivity of the system is limited by the particular current amplifier and the microwave setup. It could be further improved by a factor 2 using baseband ADC with higher resolution. Our analysis shows that NEP ~ 10^{-15} W/Hz$^{1/2}$ is feasible with already existing well-isolated THz TES and MKING with improved design and back-end electronics. The obtained values of Q factor of resonator in current amplifier allow to scale up detector system to >100 pixel per readout channel at 4.2 K.

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