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Towards a dc SQUID read-out for the normal metal hot-electron microbolometer

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Abstract

A prototype of SQUID read-out for current measurements at the output of a normal metal hot-electron microbolometer has been developed and tested. The system is based on serial VTT dc SQUID and input μ-metal core solenoid transformer. The achieved current resolution is 300 fA/Hz$^{1/2}$. Johnson noise of metal resistor and shot noise of tunnel junction were used for current calibration of SQUID read-out. The current noise spectra of 35 kΩ SIN tunnel junction measured at different bias voltages are presented.

Keywords: dc SQUID; SIN tunnel junction; SQUID femtoamperemeter

1. Introduction

Normal metal hot-electron microbolometer (NHEB) is a novel superconducting device for radiation detection at ultimately low level. It consists of a normal metal microstrip connected to superconducting electrodes by direct SN contacts, or tunnel SIN junctions [1]. First type is called bolometer with Andreev reflection (ANHEB), and the second—a capacitive reflection bolometer (CNHEB). For normal metal strip temperature measurements an additional SIN tunnel junction is connected to the strip in ANHEB, or inherent contacting SIN junctions are used in CNHEB [2]. In a voltage-bias mode the device is characterized by current responsivity $S_I = \delta I_\omega / \delta P_\omega$, where δP_ω is the Fourier component of the small variation of the external RF power, and δI_ω is the current response. Finally, the noise is characterized by a noise equivalent power NEP, which is the net effect of all noise sources referred to the input of the device. In order to reach the NEP $= 10^{-18}$ W/Hz$^{1/2}$ the noise of read-out system δI_ω should be below 50 fA/Hz$^{1/2}$.

The most sensitive current meter is SQUID-based femtoamperemeter. As it was demonstrated

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in Ref. [3] the equivalent input current noise of about 4 $fA/Hz^{1/2}$ can be reached. Such system is based on a cryogenic current comparator and allows to reach ultra-low current noise with commercial Quantum Design SQUID [4]. The main disadvantages of such approach are relatively big size and weight of device: cryogenic part with superconducting shields has 80 mm diameter and 200 mm high.

Another integral SQUID compatible solutions are using a superconducting planar transformer [5] or a current transformer with ferromagnetic core. The last case is easy for realization and can be the first step towards the SQUID read-out for the NHEB.

2. Preliminary estimations

In our NHEB bolometer SIN tunnel junction is a temperature sensor. It is dc voltage biased (via resistor $R_v \ll R_n$) at sensitive bias point. A small variation of the external RF power produce the current response δI_ω, which goes through a primary winding of SQUID read-out input transformer. The SQUID output signal is proportional to this current.

Nonlinear I–V curve of SIN tunnel junction can be approximated by an analytic relation. For voltages below the energy gap relation can be reduced to [6]:

$$I = \frac{V}{R_0} + \frac{\sqrt{2\pi\Delta kT}}{2eR_n} \exp\left(-\frac{\Delta - eV}{kT}\right), \tag{1}$$

where R_n is the normal state resistance, R_0 the zero-bias resistance, k—Boltzman's constant, T—electron temperature in the normal electrode, Δ—superconductor energy gap. For noninvasive measurements of the temperature SIN junction should be small enough compared to the strip size that limits the junction dimensions to about $0.2 \times 0.2\ \mu m^2$. Such tunnel junction optimized for NHEB ultimate performance should have normal resistance in the range 1–10 kΩ. Variations of current to be read-out are in the range 10–100 $fA/Hz^{1/2}$.

To estimate the SQUID read-out performance, one can consider the energy domain. Two reduced expressions

$$\varepsilon_m = L_i\,\delta I_\omega^2/2, \tag{2}$$

$$\varepsilon_{SQ} = S_\Phi/2L_{SQ} \tag{3}$$

give the magnetic energy produced by the noise current δI_ω and energy resolution ε_{SQ} of the SQUID. For the optimal performance when coupling factor k between the input inductance L_{in} and the SQUID is ~1 these energies should be equal. The calculated SQUID parameters and L_{in} for estimation of current sensitivity are given in Table 1.

Table 1 is divided into two parts by energy resolution ε. The energy is given in $J/Hz^{1/2}$ and in Planck's constant h. There are SQUID parameters to the left side and input parameters to the right side. The top left half-row presents the fixed SQUID self-inductances L_{SQ}. The left data field presents the SQUID magnetic flux sensitivity S_Φ, which can be obtained for real device. This value

Table 1
Current sensitivity of SQUID readout for different loop and input coil inductances

SQUID parameters					ε (h) (J/Hz)	Input coil parameters						
L_{SQ} (pH)	10	40	160	640		316	100	31	10	3.1	1	δI_ω $(fA/Hz)^{1/2}$
$S_\Phi^{1/2}$ $\mu\Phi_0/Hz^{1/2}$	3.16	6.3	12.6	25	3220 21×10^{-31}	0.042	0.42	4.2	42	420	4200	L_{in} (mH)
	1	2	4	8	322 2.1×10^{-31}	0.004	0.042	0.42	4.2	42	420	
	0.31	0.63	1.2	2.5	32 0.21×10^{-31}	0.4×10^{-3}	0.004	0.042	0.42	4.2	42	
	0.1	0.2	0.4	0.8	3.2 0.02×10^{-31}	0.04×10^{-3}	0.4×10^{-3}	0.004	0.042	0.42	4.2	

depends on SQUID parameters, room-temperature electronics, SQUID temperature, etc. Corresponding energy resolution is given in the middle column. The top right half-row presents the fixed noise current resolution δI_ω, which is desirable to obtain. The right data field gives the necessary input inductance L_{in} to get the corresponding δI_ω. Note that results from Ref. [3] are in a good agreement with energy calculations.

3. SQUID read-out design

Cryogenic mount assembly is shown in Fig. 1. It was designed for testing of SQUID, input transformers and NIS junctions. All these parts are placed on a printed circuit plate with 12-pin connector. This plate can be placed in He^3-cryostat in a future. The VTT SQUID [7] is bonded on a special circuit board and placed in a socket on the plate. A small bulk transformer with diameter 2 mm and length 6 mm is placed near the SQUID circuit. The whole probe is shielded with a lead screen.

The transformer has 300 turns primary coil wound of 36 μm diameter copper wire on soft magnetic core 0.4 mm in diameter and 6 mm long. The second superconducting coil with five turns wound above primary is connected to input coil of the SQUID. The SQUID and integrated input coil have inductances $L_{SQ} = 8$ pH and $L_{in} = 340$ nH, respectively. The input current of approximately 3 μA yields a SQUID response of one flux quantum.

The block diagram of the SQUID read-out is shown in Fig. 2. VTT nonmodulation electronics is used to operate SQUID [8]. The preamplifier intrinsic noise is about 1 nV/Hz$^{1/2}$. The operation in closed loop mode is limited within one flux quantum in order to avoid output level hopping due to external disturbances. To verify current-to-flux transfer coefficient it was used standard sinusoidal signal source.

4. Experimental results

To test and calibrate SQUID read-out as the first step we have measured the spectral density of

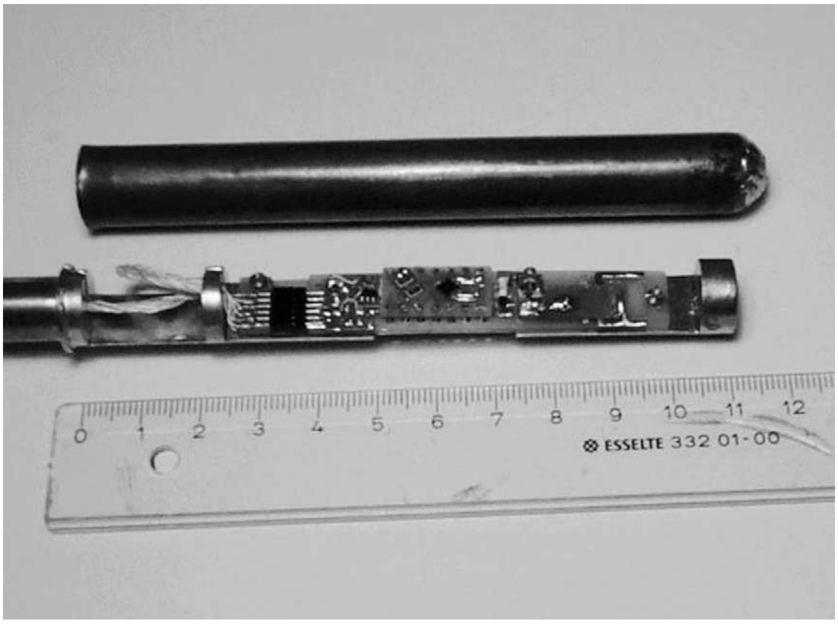

Fig. 1. Cold part of the dip probe with plate for SIN sample.

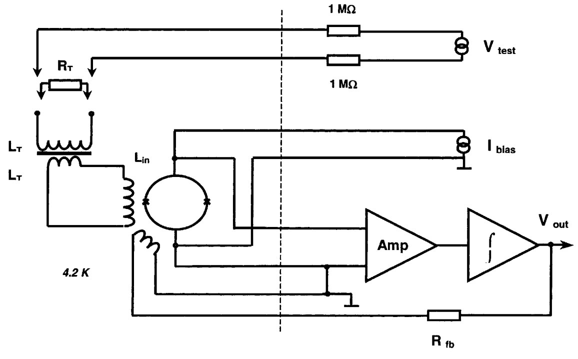

Fig. 2. Block diagram of the SQUID read-out.

the SQUID read-out with opened SQUID input coil. The resulting spectrum is shown in Fig. 3, curve 1. White flux noise level in flux locked loop mode turned out to be 3 $\mu\Phi_0/\mathrm{Hz}^{1/2}$. Intrinsic energy resolution corresponding to this noise is approximately $\varepsilon_{SQ} = 3 \times 10^{-30}$ J/Hz$^{1/2}$. The bandwidth is over 100 kHz.

As the next step we attached μ-metal transformer to the input coil and measured the current-to-flux transfer coefficient applying a small ac current to the primary winding of the transformer. The input current of approximately 100 nA yields a SQUID response of one flux quantum. The test noise measurements were made with three cooled resistors 10 kΩ, 100 and 10 Ω. Corresponding spectra are presented in Fig. 3 as curves 2, 3 and 4 respectively. Lines 5, 6 and 7 correspond to values of Johnson current noise of these resistors $\delta I_\omega = (4kT/R)^{1/2}$ at 4.2 K. In all cases the increase of white noise level is in good agreement with the theory. The curve 2 obtained with 10 kΩ resistor demonstrates noise of the SQUID read-out system, because the Johnson noise of 10 kΩ is twice as low compared to that of SQUID read-out. The equivalent current white noise level is below 0.3 pA/Hz$^{1/2}$. An additional low-frequency noise at frequencies below 800 Hz can be due to additional noise produced by permalloy core. This noise can be attributed to the Barkhausen effect in core made of soft ferromagnetic material [9]. For 10 Ω resistor (curve 4) the frequency bandwidth is decreased, because the cut-off frequency of *R–L* input circuit becomes less than frequency bandwidth of the SQUID electronics. The calculation of equivalent L_{in} brings 66 μH. At 300 K the L_{in} value was 260 μH.

The next measurements were performed with standard Al–AlO$_x$–Cu SIN temperature sensors that bring the linear *I–V* curve at LHe temperature. Our SIN junctions have a normal resistance about 35 kΩ. The noise spectra of this SIN junction were measured at different bias voltages V_b. Results are presented in Fig. 4. The curve 1 was

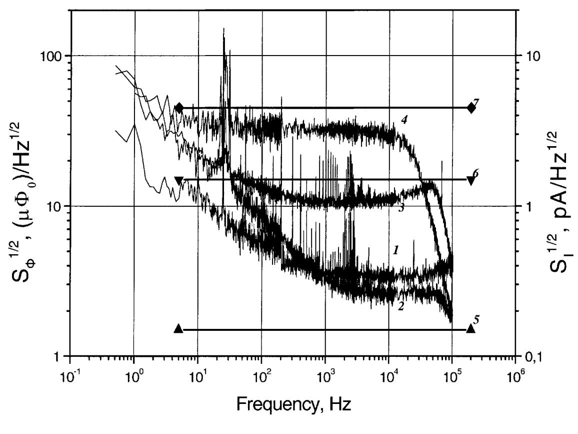

Fig. 3. Equivalent current/flux noise spectra of the SQUID read-out: curve 1—noise of the system without transformer; curve 2, 3, 4—SQUID read-out with transformer and input resistors 10 kΩ, 100 and 10 Ω, respectively; lines 5, 6, 7—calculated Johnson's current noise of the 10 kΩ, 100 and 10 Ω resistors.

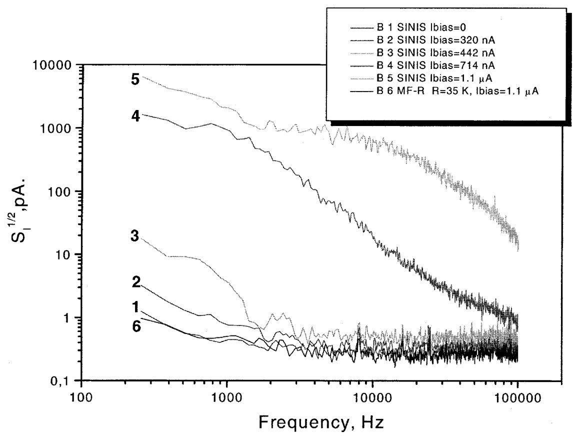

Fig. 4. Current noise spectra of the 35 kΩ SIN tunnel junction measured using SQUID read-out at $V_b = 0$, 11, 15, 25, 38 mV, (curves 1–5). Curve 6—noise spectrum with 35 kΩ metal film resistor at the $V_{b5} = 38$ mV.

obtained at $V_b = 0$ and equivalent the second curve in Fig. 3. At $V_{b1} = 11$ mV, at which current I through the SIN junction was 320 nA the noise of SIN junction exceeds the SQUID read-out noise. At $V_{b2} = 15$ mV the SIN junction white noise was 0.5 pA/Hz$^{1/2}$ (curve 3). In this bias region V_b the white noise level of the measured spectra is in agreement with Shottky formula: $S_I = 2eI$. Above $V_{b3} = 16$ mV the excess noise was observed in SIN junction. The corresponding spectra measured at $V_{b4} = 25$ mV and $V_{b5} = 38$ mV are given by curves 4 and 5, respectively. For testing of our system in voltage bias mode the additional spectrum with 35 kΩ metal film resistor (spectrum 6) and the same $V_{b5} = 38$ mV was measured. This noise did not exceed the SQUID read-out noise.

5. Conclusion

The tests of SQUID read-out with standard VTT SQUID and small permalloy transformer demonstrate the equivalent current resolution of 300 fA/Hz$^{1/2}$ in more than 100 kHz bandwidth. This result is in a agreement with the energy resolution of the system calculated from SQUID energy resolution and input transformer self-inductance. An improving of the current sensitivity of the SQUID read-out down to 30 fA/Hz$^{1/2}$ can be achieved by increasing of the input transformer self-inductance to 600 μH and decreasing of the SQUID flux noise down to 1 $\mu\Phi_0$/Hz$^{1/2}$.

Acknowledgements

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