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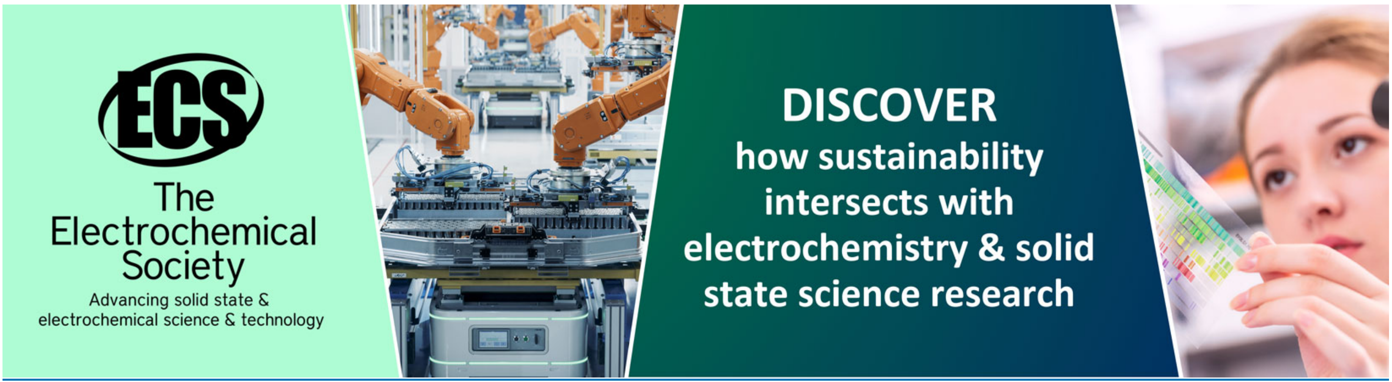

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Absolute Power Measurement with Transition Edge Sensors and SQUID Amplifier

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Abstract. We have developed a new cryogenic radiometer for determining absolute power. This instrument is composed of a superconducting transition edge sensor as a thermometer, a silicon substrate as a heat absorber, and a SQUID amplifier as a readout. The input power is measured with electrical substitution of a heater on the device. By using very sharp transition of the thermometer, the device temperature is locked within its transition temperature. This device demonstrated very wide dynamic range of more than 10^5, very low noise equivalent power of 1.5 nW. These properties are very attractive to be used as highly precise power measurement instruments in metrological fields.

1. Introduction

A determination of absolute power such as laser, optical intensity, and ac modulated voltage/current signal is getting more important in industry. Currently various types of power meters are used to measure the power values, however, these power meters need calibration with very reliable instruments which give an absolute power value. In order to define the absolute power, cryogenic radiometers[1] or thermal converters[2] are frequently used. Basically these devices consists of a heat absorber, a thermometer, and an electrical heater onto a single thermal node. This node is isolated from a heat sink with well-defined thermal conductance, and biased at certain temperature by inducing known electrical power to the heater. Unknown input power, which we want to define with the minimum uncertainty, is measured using an electrical substitution method. In the method, the node temperature is always fixed by changing the heater power on the node, thus the unknown input power is measured as the difference of the heater power when the unknown power is on and off.

The current cryogenic radiometers are now used as a primary standard at most national metrology institutes, and supplying various types of power scale. However they have some drawbacks such as narrow dynamic range, limitation of minimum measurable power to several hundred micro watt, very slow response time of a few minutes, remarkable drift of the baseline. To overcome these restrictions, we have developed a new cryogenic radiometer with a superconducting transition edge sensor (TES) and a superconducting interference device readout(SQUID). The transition of the TES between the superconducting and normal state occurs typically within tens mili Kelvin, which is very useful to lock the device temperature in the electrical substitution. The SQUID readout will enable us to readout TES current change at low power level measurement. In the present proceeding, we firstly report the performances obtained by our prototype device. We hope that this device will lead to an introduction of a next generation technique of a primary standard for power measurement calibrations.

2. Device Configuration

A design of the power sensing device is shown in figure 1. The chip substrate is silicon wafer of 380 μm width and its size is 9×9 mm^2. A SiN film is deposited on the both side of the wafer for electrical isolation. A superconducting niobium TES film is placed at the center of the chip. The normal resistance of the TES is 13 Ω. The TES shows very sharp superconducting-normal transition at 9.5K with 10 mK transition width. Two aluminium heater 1 and 2 are placed around TES on the chip. The heater 1 is used to raise the chip temperature to the transition temperature of TES. The heater 1 is also used to substitute the input power. The heater 2 is used to induce the input power. Typical resistance of both heaters is 900 Ω. This chip is suspended with 16 aluminium bonding wires to thermally isolate the chip from a heat sink. The diameter of the aluminium bonding wire is 25 μm. The temperature of the heat sink is stabilized at 4.5 K with a PID temperature controller.

The diagram of the electrical substitution is shown in figure 2. For the stable operation, the TES is voltage biased with a 0.1 Ω shunt resistance. The current change caused by resistance change of the TES is read by 200-series SQUID amplifier. The typical current-voltage conversion gain of the SQUID is 800 (V/A). The SQUID output is feed-backed to lock the device temperature to the TES transition temperature. We call this feedback TLL (Temperature Locked Loop).

The input power P_{input} is measured with the electrical power substitution of the heater 1. For the equilibrium state with no input power to the heater 2, the thermal equation of the device can be written as

$$P_1 = G(T_1 - T_{\text{bath}}), \tag{1}$$

where G is thermal conductance to the heat bath, T_{bath} is the bath temperature, P_1 is Joule heating power and of heater 1, and T_1 is the temperature of the chip. When the input power P_{input} is induced to the heater 2, the thermal equation can be written as

$$P_2 + P_{\text{input}} = G(T_2 - T_{\text{bath}}), \tag{2}$$

where P_2 and T_2 is the power of heater 1 and the temperature of the device, respectively. Thus, if the temperature of the device is locked to the transition temperature of the TES during these processes, P_{input} can be simply obtained as

$$P_{\text{input}} = P_1 - P_2. \tag{3}$$

We repeated number of measurements of P_{input} to evaluate the precision of the device. The uncertainty (Type A) of P_{input} is derived from the standard deviation in the measurements.

3. Experiment and Result

3.1. Open loop

Firstly, we have measured a static property of the device without TLL. Figure 3 shows the transition behaviours of the TES to the bias power of the heater 1. Two curves are drawn in the figure; the right curve is the transition for no-input power to the chip, and the left curve is with the input power $P_{\text{input}} = 10$ μW to the chip by applying Joule heating to the heater 2. These experiments were performed at the base temperature of 4.5 K. The TES resistance has greatly changed at $P_1 \approx 305.75$ μW and $P_2 \approx 295.75$ μW for both curves, and the difference of

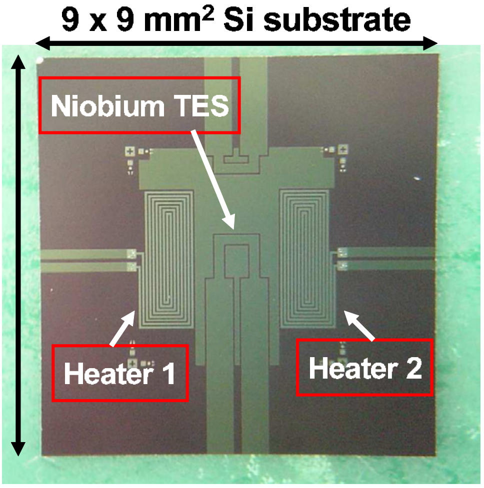

Figure 1. Absolute power measurement device with a niobium TES and two aluminium heater.

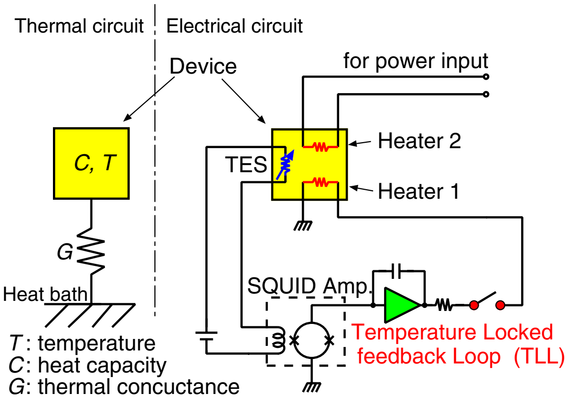

Figure 2. Experimental setup for power measurement with temperature locked feedback loop.

$P_1 - P_2$ is almost the same with $P_{\rm input}$. The slope during the transition is 9.25×10^7 Ω/W at $R = 7$ Ω, which means very high open loop gain is achieved. The value of P_1 is determined to raise the device temperature to T_c of Nb TES. From this observation, the thermal conductance G is calculated to 87.3 μW/K.

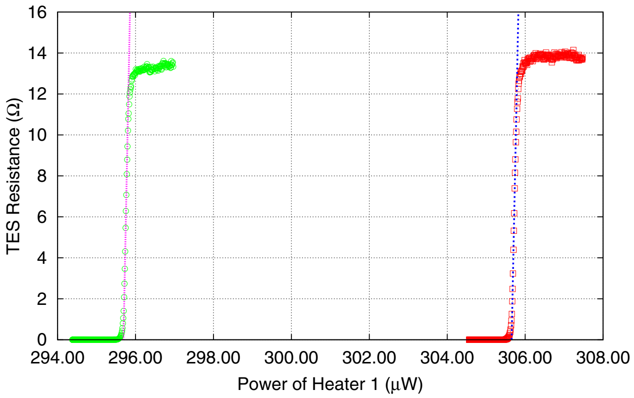

Figure 3. Static property of TES transition without TLL. The right curve is the transition for no-input power, and the left curve is for $P_{\rm input} = 10$ μW. Two broken lines in the figure for both curves are the results of a linear fitting during the transition for each curve.

3.2. Closed loop

We have closed the feed-back loop to stabilize the device temperature and measured the power dissipation of the heater 1. The variation of the heater power during 250-second period is shown in figure 4. The data were measured every 0.5 second. The average power of data is 305.569 μW, and the standard deviation is 1.5 nW.This means that the device power was stabilized within the order of a few nano watt. From this result, the uncertainty of power measurement can be roughly expected to $\sqrt{2} \times 1.5$ nW for the power range from a few nW to 300 μW. Thus, very low noise can be achievable for wide dynamic range of the input power.

To endure this, the known input power was induced to the heater 2 on the chip, and the substituted power of the heater 1 was measured using (3). The results are shown in figure 5.

The substituted power of the heater showed perfectly linear relation to the input power to the heater 2 for 10^6 power range.

The switching properties of TLL were measured by inducing step input to the heater 2. The obtained time constant of the heater 1 is 94.8 μs for power on, and 56.4 μs for power off of the heater 2, respectively. We have estimated the loop gain from these results. The intrinsic time constant $\tau = C/G$, where C is the heat capacity of the device, is estimated to 1.3×10^{-5} J/K. The effective time constant with TLL can be obtained by $\tau_{\mathrm{eff}} = \tau/(1 + \mathcal{L}_0)$, where $\mathcal{L}_0$ is a loop gain at zero frequency. Thus, $\mathcal{L}_0$ of TLL is estimated to over 1500. This will greatly increase the speed of the device, and reduce the measurement time. It is worthy to note that this high speed readout is very attractive for determination of the power in metrology because it will greatly reduce drift effect of the radiometers.

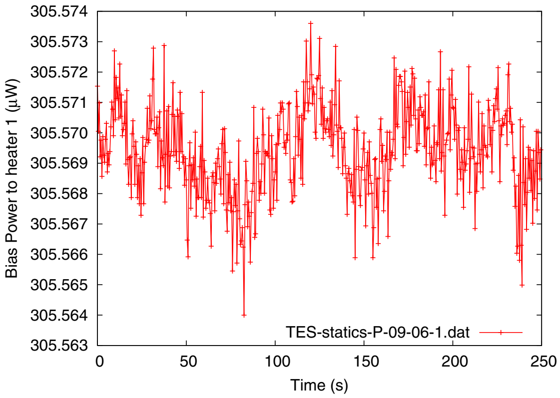

Figure 4. Heater 1 power variation with time. The data is measured every 0.5 s. The average is 305.569 μW, and the standard deviation is 1.5 nW.

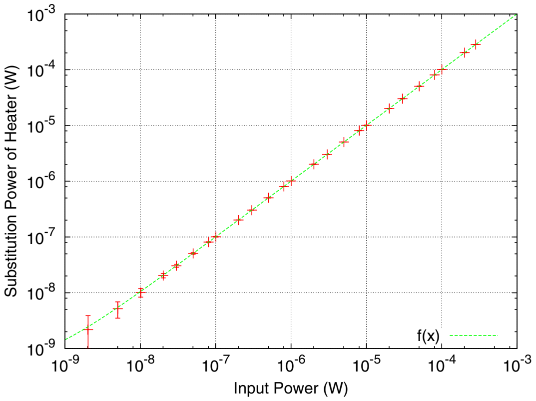

Figure 5. Power measurement results by inducing known power to heater 2. The obtained substituted power is perfectly linear to the input over 10^5 range.

4. Conclusion

We have demonstrated a new device with a transition edge sensor and a SQUID readout to determine the absolute power.

In the operation TES locked the device temperature within its transition temperature and made the electrical substitution work well. The device showed very low noise equivalent power of 1.5 nW, over 10^5 dynamic range, and very fast response within 0.1 ms time constant. We think these results are very encouraging for future development of highly precise primary standards of the power measurement.

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References

[1] T. R. Gentile, J. M. Houston, J. E. Hardis, C. L. Cromer, and A. C. Parr. National institute of standards and technology high-accuracy cryogenic radiometer. *Appl. Optics*, 35(7):1056–1068, 1996.

[2] T. E. Lipe, J. R. Kinard, and C. D. Reintsema. Improvements in the nist cryogenic thermal transfer standard. *IEEE Trans. Instrum. Meas.*, 50(2):326–329, 2001.