# Excess Noise in Superconducting Bolometers*†

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A large excess of noise above that expected on the basis of thermal fluctuations has been observed in the output of thin-film Sn superconducting bolometers. The noise spectrum has been measured from 50 Hz to 4 MHz, with an additional measurement at 30 MHz as a function of applied magnetic field. The excess noise in the 100 KHz to 30 MHz range is found to be damped by the application of a perpendicular field of from 3 to 15 G. There is a $1/f^2$ component at lower frequencies which is believed to be due to the detection of acoustic bubbling in the liquid helium. This portion of the noise was not affected by the application of a magnetic field.

## I. INTRODUCTION

ALTHOUGH some thermal detectors have been developed to the point where the lower limit of radiation detection is set by the unavoidable thermal fluctuations in the detector element, the sensitivity of the superconducting bolometer has been limited by excess electrical noise.[1,2] Superconducting bolometers have been fabricated with a noise equivalent power (NEP) of $10^{-11}$ W/Hz$^{1/2}$ and a thermal time constant $\tau$ of 18 nsec. As these devices are potentially quite useful, it is important to understand the factors contributing to this limit. Furthermore, this noise may provide information on some of the physical processes occurring in the superconducting-to-normal phase transition. This paper presents experimental results on the excess noise level observed in the output of Sn thin-film superconducting bolometers in the frequency range 100 Hz–4 MHz and in the presence of an applied perpendicular magnetic field. A brief description of the expected noise sources in superconducting bolometers is also presented.

## II. CLASSICAL NOISE SOURCES IN SUPERCONDUCTING BOLOMETERS

There are at least two fundamental sources of noise in a bolometer: Johnson noise, associated with its resistance and temperature; and the unavoidable temperature fluctuations, caused by the statistical exchange of energy between the detection element and its surrounding thermal reservoir. The mean-square voltage for Johnson noise is

$$\langle v_j^2\rangle = 4kTRB\,, \qquad (1)$$

where $k$ is Boltzmann's constant, $T$ is the temperature of the detector element, $R$ is the resistance, and $B$ is the bandwidth of the detecting system. The noise power is equivalent to an external radiation input $W_j$, where

$$\langle W_j^2\rangle = \langle v_j^2\rangle / r^2\,, \qquad (2)$$

where $r$ is the responsivity of the bolometer in V/W.

The noise attributable to the temperature variations has been discussed by Smith and his co-workers[3] and by Martin and Bloor.[4] For a body in thermal equilibrium with a heat reservoir the mean-square temperature fluctuation can be shown[3] to be

$$\langle \Delta T^2\rangle = kT^2/C_v\,, \qquad (3)$$

where $C_v$ is the specific heat capacity of the body.

Since the bolometer has a nonzero $\partial R/\partial T$, we obtain an equivalent incident thermal noise power of

$$\langle W_T^2\rangle = 4kT^2GB\left(1-\frac{I^2}{G}\frac{\partial R}{\partial T}\right), \qquad (4)$$

where $G$ is the thermal conductance of the body to the surroundings, and $I$ is the dc current of the bolometer. One might note that these two sources are both located at an external plane of reference. The "thermal" noise of Eq. (4) will not be observable in the absence of a detector bias current, whereas the Johnson noise is always present.

As these noise sources are statistically independent, the mean-square values will add to give the total equivalent noise source $W_n$:

$$\langle W_n^2\rangle = 4kTB\left[GT\left(1-\frac{I^2}{G}\frac{\partial R}{\partial T}\right)+\frac{R}{r^2}\right]. \qquad (5)$$

For bolometers with a sufficiently high responsivity, the term representing the Johnson noise may be neglected in comparison with the thermal-noise contribution. The superconducting bolometers discussed in this paper satisfy this condition with the ratio of thermal-to-Johnson noise always being at least 100:1. This treatment assumes that the detector is operating in the transition region where $\partial R/\partial T$ is large.

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† Work based on a thesis (M. K. M.) submitted to the Massachusetts Institute of Technology in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Electrical Engineering.
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[1] D. H. Andrews, R. M. Milton, and W. DeSorbo, J. Opt. Soc. Am. **36**, 518 (1946).
[2] N. Fuson, J. Opt. Soc. Am. **38**, 845 (1948).
[3] R. A. Smith, F. Jones, and R. Chasmar, in *The Detection and Measurement of Infrared Radiation* (Clarendon Press, Oxford, England, 1957).
[4] D. Martin and D. Bloor, Cryogenics **1**, 159 (1961).

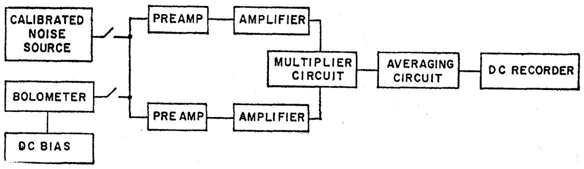


FIG. 1. Block diagram of the correlation detector.

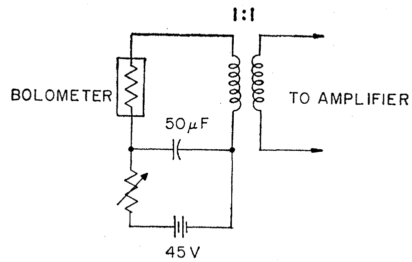


FIG. 2. Bias circuit for the bolometer.

## III. EXPERIMENTAL

As the noise from the amplifier following the detector is greater than that expected from a bolometer at liquid-helium temperatures, a cross-correlation circuit of the Brown-Twiss[5] type was used to observe the bolometer noise. This system can detect signals that are small in comparison with the noise levels of the amplifiers used in the system. A block diagram of this system is shown in Fig. 1.

Each channel has a gain of 90 dB over a frequency range 100 kHz–4 MHz. The bolometer under test is biased by connecting it in series with a 45-V battery and a resistance that is large compared with the bolometer resistance, as shown in Fig. 2.

The noise was calibrated by using a Johnson noise source (a resistor at room temperature). At frequencies from 100 Hz to 40 kHz the noise levels were sufficiently large that the correlation system was not needed. A tuned amplifier followed by a detector was used in this range. Spot measurements were made at 30 MHz using i.f. amplifiers manufactured by RHG Inc., instead of the 100 kHz–4 MHz amplifier.

The bolometers were of high purity Sn, evaporated onto single-crystal polished sapphire substrates at a rate of 50 Å/sec and at pressures of less than $10^{-5}$ Torr. The bolometer geometry is shown in Fig. 3 with the top and bottom areas being contacts. The thickness of the central area was typically of the order of 1000 Å, as measured by a quartz-crystal microbalance. The horizontal lines were scribed with a sharp point to produce a higher electrical resistance between the contacts. The film width between the scribed lines was 0.75–1.0 mm. The thermal conductance G to the surroundings was typically 1 W/°K cm$^2$. This is principally the thermal conductance to the substrate, since the thermal conductance to the liquid helium was 0.2 W/°K cm$^2$. Values of $\partial R/\partial T$ were from $3\times10^3$ to $10^4\Omega$/°K. The thermal time constant varied from 17 to 29 nsec. Films were evaporated onto substrates either at room temperature or liquid-nitrogen temperature with similar noise levels being found in each case.

## IV. EXPERIMENTAL RESULTS

Measurements of the dc resistance transition and the noise level $V_n(T)$ as a function of temperature for various values of applied magnetic field are illustrated in Figs. 4–6. A noise curve $V_c(T)$ calculated from Eq. (6) (using the experimental values of bias current, thermal conductance, the magnetic field, and $\partial R/\partial T$) is superimposed on Figs. 5 and 6 for purposes of comparison. The noise appears only in the transition region. The peak in noise as a function of temperature appeared slightly below that predicted on the basis of the responsivity at zero field while coinciding with it at fields ranging from 3 to 15 G. With this field variation, the noise level in the 100 kHz–4 MHz range decreased from a level in zero field ~10 dB above that calculated for thermal noise to a level closely approximating the theoretical thermal noise. The excess noise levels were as high as 20 dB in some bolometers. The low-frequency portion of the spectrum includes a $1/f^2$ component[6] which was not affected by the magnetic field. At 100 kHz, the spectral density of this noise is typically 10 dB above the spectral density of the normal thermal fluctuation noise. This $1/f^2$ portion of the noise spectrum decreased greatly (20 dB at frequencies less than 20 kHz) when the bolometer was operated out of the helium bath or when immersed, if the temperature was below the λ point of the helium bath. In parallel magnetic fields, the behavior of the noise level was similar to that of the perpendicular case if the enhancement of the critical field was considered.[7] When the bandwidth of the 100 kHz–4 MHz amplifiers was reduced to 100 kHz–2 MHz using low-pass RC filters,

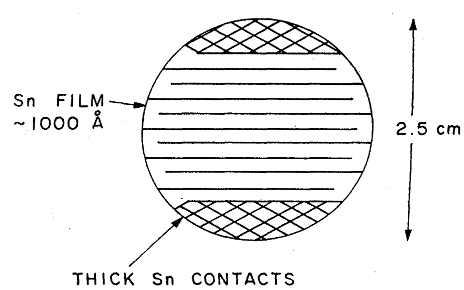


FIG. 3. Bolometer geometry.

[5] R. H. Brown and R. W. Twiss, Nature 177, 24 (1956).

[6] M. W. P. Strandberg and J. D. Kierstead, M. I. T. Research Laboratory of Electronics Quarterly Progress Report No. 82, 1966, pp. 11–12 (unpublished).

[7] R. Deltour and M. Tinkham, Phys. Rev. Letters 19, 125 (1967).

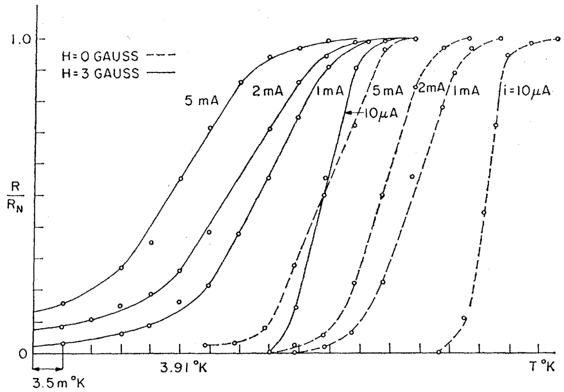


FIG. 4. Resistance transition with bias current and magnetic field as parameters.

the integrated noise power decreased by approximately 3 dB. The measurements at 30 MHz preserved the same ratios between the excess noise in zero field to the thermal noise. Calibration measurements indicate a decrease in noise/Hz at 30 MHz of 12 dB in agreement with the measured time constant. The results of four-point measurements of the noise were similar to those obtained with the current and voltage measured at the same terminals.

## V. DISCUSSION

There has been no discussion in this paper of the upper frequency cutoff of the thermal noise. This topic has been treated in a concurrent paper,[8] which deals with the incremental impedance and equivalent circuit of superconducting bolometers. This treatment shows that the thermal noise spectrum should be constant at low frequencies and be of the form

$$\langle V_T^2\rangle = \frac{4kT^2GI^2(\partial R/\partial T)^2\Delta f}{[G-I^2(\partial R/\partial T)]^2+\omega^2 C_v^2}, \tag{6}$$

with an upper frequency cutoff of

$$\frac{\omega_c}{2\pi} = f_c = \frac{[G-I^2(\partial R/\partial T)]}{2\pi C_v}. \tag{7}$$

For the bolometers investigated, this was approximately 8 MHz. This would be above the system response for the 100 kHz–4 MHz amplifiers.

The 3-dB decrease in integrated noise power observed for a 50% reduction in amplifier bandwidth indicates that the high-frequency noise spectrum is not of the $1/f^2$ form found at lower frequencies. Although we cannot completely rule out a much slower variation with frequency in this range, such as a $1/f^x$ where $x<1$, it seems reasonable that the spectrum is relatively uniform at frequencies up to $f_c$.

As the low-frequency component of the noise spectrum is so much smaller in the nonbubbling helium, we assume that this portion of the power spectrum is due to the detection of acoustic or thermal noise produced by the bubbles. A similar form of noise has been noted[9] in copper-doped germanium bolometers.

The excess noise at high frequencies fits the form

$$\langle V_n^2\rangle = \frac{4kT^2GI^2[\partial R(H,T)/\partial T]^2[1+f(H,T)]\Delta f}{[G-I^2(\partial R/\partial T)]^2+\omega^2 C_v^2}, \tag{8}$$

where the effects of the responsivity and the thermal-noise level are the first portion of this expression. The excess noise contribution has been placed in the function $f(H,T)$ which reduces to zero at higher magnetic fields. The temperature dependence of $f(H,T)$ is such that the maximum noise power occurs at a temperature slightly below the temperature for maximum $\partial R/\partial T$. This may be represented by a thermal-noise source with a temperature

$$T_n = T[1+f(H,T)]^{1/2}. \tag{9}$$

The measurements at 30 MHz indicate that the spectrum of this excess noise has the same frequency dependence as the thermal noise; that is, it has a high-frequency cutoff, $f_c$, given by Eq. (7).

We have speculated about a mechanism that might generate such an excess noise spectrum, but have not reached any conclusions. The question of whether the noise is a fundamental property of the superconducting-to-normal phase transition or a property of the thin-film structure has not been settled. The strategy adopted in interpreting the experimental results was based upon the use of the Callen-Welton fluctuation-dissipation

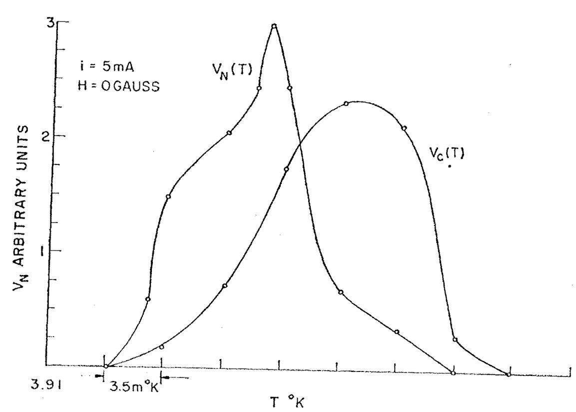


FIG. 5. Bolometer noise at 0 G as a function of temperature.

[8] M. K. Maul and M. W. P. Strandberg, J. Appl. Phys. 40, 2822 (1969).

[9] G. Baker and D. Charlton, Infrared Phys. 8, 15 (1968).

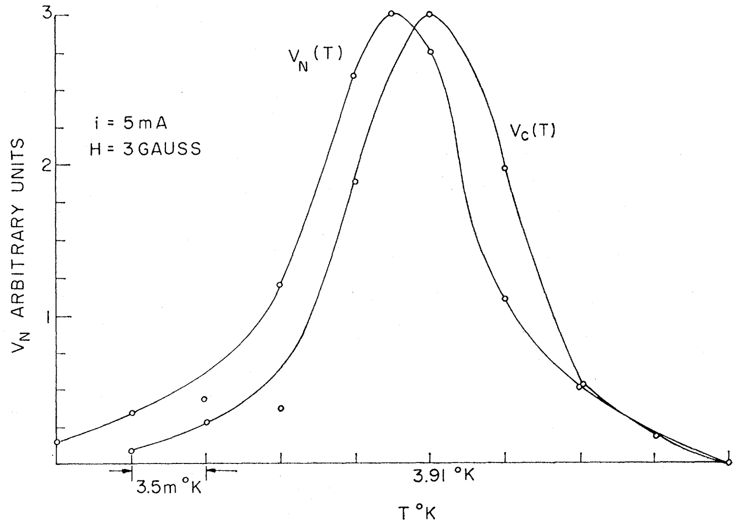


FIG. 6. Bolometer noise at 3 G.

theorem. Johnson noise and temperature-fluctuation spectra are readily derived by using this theorem with voltage and current, and entropy and temperature as the extensive and intensive parameters. But we have been unable to include the magnetic field in such a way as to enhance the temperature fluctuation at zero field. Furthermore, we do not see how to use the calculations of the impedance of superconducting films by Caroli and Maki,[10] for example, to produce an additional temperature fluctuation that is quenched by the application of a magnetic field.

The shift of the maximum of the anomalous noise spectrum to temperatures below the maximum of $\partial R/\partial T$ may be significant. If one views the transition resistance change as a gradual increase in the resistivity of the superconducting electrons, through order-parameter fluctuation, then the low-temperature portion of the transition resistance curve is dominated by superconductivity effects. The high-temperature portion of the resistance transition curve is dominated by normal electron conductivity, since the electromagnetic field interacts with normal electrons predominantly when the superconducting electron conductivity in parallel with normal electron conductivity approaches zero. Thus, one is tempted to conclude that the anomalous noise is a superconducting effect, although the argument is admittedly tenuous.

[10] C. Caroli and K. Maki, Phys. Rev. **159**, 306 (1967).

## VI. SUMMARY

Excess noise was observed in the noise-power spectrum of thin-film Sn superconducting bolometers when operated in zero field. This noise was damped by the application of a perpendicular field of a few gauss and observed only in the transition region. The remainder was that calculated on the basis of thermal fluctuations in the bolometer element. The parallel-field dependence of the excess-noise levels was similar to that of the perpendicular case if the enhancement of the critical field with this orientation was considered. The frequency dependence of this spectrum was found to be similar to that of the thermal-fluctuation noise. The $1/f^2$ component at the lower frequencies is due to the detection of acoustic noise in the bubbling helium. Neither of these components was due to contact noise, as shown by the equivalent results obtained from four-point measurements. The presence of the excess noise is not affected by the grain size in the film, as can be inferred from similar noise spectra measured with films evaporated onto liquid-nitrogen-cooled and room-temperature substrates.

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