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FLICKER (1/f) NOISE IN JOSEPHSON TUNNEL JUNCTIONS

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DISCLAIMER

FLICKER (1/f) NOISE IN JOSEPHSON TUNNEL JUNCTIONS*

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ABSTRACT

We have measured the power spectrum of the voltage fluctuations in

shunted Josephson junctions biased at a constant current I greater than

the critical current I_c. Over the frequency range 5×10^{-2} to 50 Hz the

power spectra vary approximately as 1/f, where f is the frequency. At

a single frequency, the noise decreases as I is increased. Experimental

evidence is presented to show that the voltage noise arises from equilib‑

rium fluctuations in the temperature T of the junction which in turn

modulate I_c, and hence the voltage V across the junction. The magnitude

of the power spectra is consistently predicted to within a factor of

5 by an extension of the semiempirical formula of Clarke and Voss:

$S_V(f) = (dI_c/dT)^2 (\partial V/\partial I_c)_I^2 \, k_B T^2 / 3 C_V f$. In this formula, we postulate

that C_V is the heat capacity of an "effective" junction volume given by

the product of the junction area and the sum of the coherence lengths

of the two superconductors. The dependence of $S_V(f)$ on $(\partial V/\partial I_c)_I^2$ and

$(dI_c/dT)^2$ is experimentally established.

I. INTRODUCTION

Apart from a passing reference by Kanter and Vernon,[1] the question

of excess low frequency noise in Josephson junctions[2] appears to have

received little attention hitherto. Nevertheless, it is important to

determine whether or not excess low frequency noise exists in Josephson

junctions because such noise may impose a limitation on the low frequency

performance of devices such as SQUIDs (Superconducting QUantum Interference

Devices). In this paper[3] we report measurements of voltage noise in

resistively shunted Josephson junctions biased at a current greater then

the critical current I_c over a frequency range from 5×10^{-2} to 50 Hz.

We find that the power spectrum varies approximately as 1/f at the lower

frequencies, and becomes white at the higher frequencies, the crossover

frequency depending on the experimental parameters. Moreover, at any

single frequency, the power spectrum decreases with increasing bias

current, and is proportional to $(dI_c/dT)^2$. These results strongly

suggest that the observed 1/f noise is generated by equilibrium tempera-

ture fluctuations in the junction which in turn induce fluctuations

in the critical current (provided $dI_c/dT \neq 0$). The critical current

fluctuations are observed as voltage fluctuations when the junction is

current-biased at a non-zero voltage. The thermal diffusion theory for

1/f noise developed by Clarke and Voss[4,5] for thin metal films can be

readily adapted to the case of Josephson junctions. We find good

numerical agreement between the predictions of this model and the measured

1/f spectra.

In Section II we briefly review and develop the relevant theory, and

in Section III we describe the experimental apparatus and techniques.

Section IV presents the experimental results and analysis, and Section V

contains our conclusions.

II.   THEORETICAL CONSIDERATIONS

In the thermal fluctuation model[4,5] for 1/f noise in thin metal films, one assumes that the film and its substrate are in thermal equilibrium at temperature T. Energy is exchanged between the film and the substrate producing a mean square temperature fluctuation in the film $\langle (\Delta T)^2 \rangle = k_B T^2/C_V$, where C_V is the heat capacity of the film. If the film has a non-zero temperature coefficient of resistance, β, there will be a corresponding resistance fluctuation. A steady current I passed through the film thereby develops a fluctuating mean square voltage $\langle (\Delta V)^2 \rangle = \bar{V}^2 \beta^2 k_B T^2/C_V$, where $\bar{V}$ is the mean voltage across the film. The power spectrum $S_V(f)$ of these fluctuations can be calculated using a diffusion model[4-6] in which the temperature fluctuations are uncorrelated in space and time: $\langle \Delta T(\underline{r}+\underline{s}, t+\tau)\Delta T(\underline{r},t) \rangle \propto \delta(\underline{s})\ \delta(\tau)$. This model does not yield a 1/f power spectrum. Clarke and Voss[4,5] assumed an empirical approach and introduced a 1/f region into the power spectrum over the frequency range $f_1 < f < f_2$, where $f_i = D/4\pi \ell_i^2$, D is the thermal diffusion coefficient, and ℓ_1 and ℓ_2 are the length and width of the film. The spectrum was assumed to be white for $f < f_1$, and to vary as $f^{-3/2}$ for $f > f_2$. The power spectrum was normalized by setting $\int_0^\infty S_V(f)df = \bar{V}^2 \beta^2 k_B T^2/C_V$. In the 1/f region, this procedure lead to a power spectrum

$$S_V(f) = \frac{\bar{V}^2 \beta^2 k_B T^2}{C_V[3 + 2\ell n(\ell_1/\ell_2)]f} \quad . \tag{1}$$

Equation (1) predicted the magnitude of the 1/f noise power spectrum observed in both metal films at room temperature and superconducting films at the resistive transition.[7]

Subsequently, Voss and Clarke[5] proposed a model in which the temperature fluctuations were spatially correlated, with $\langle \Delta T(\underline{r}+\underline{s}, t+\tau)\Delta T(\underline{r}, t)\rangle \propto \delta(\tau)/|\underline{s}|$. This model yielded an explicit $1/f$ region in the power spectrum for $f_1 < f < f_2$ that differed from Eq. (1) only by a numerical factor close to unity. It should be noted, however, that the measured $1/f$ region sometimes extended to frequencies below f_1. The theoretical difficulty of determining the range of frequencies over which the $1/f$ power spectrum extends has been discussed elsewhere,[5] and is not likely to be resolved until a more microscopic model of the noise becomes available that takes into account the thermal inhomogeneities of the metal-on-glass system. From an empirical point of view, this problem is not very serious since the ratio f_1/f_2 enters logarithmically. A reduction in f_1 by many orders of magnitude makes a relatively insignificant change in the value predicted for $S_V(f)$.

The thermal fluctuation model is readily adapted to noise in a Josephson tunnel junction. We shall consider junctions having a non-hysteretic current-voltage (I-V) characteristic. This requirement implies that the hysteresis parameter[8] $\beta_c = 2\pi I_c R^2 C/\phi_o \lesssim 1$, where R is the resistance shunting the junction, C is the junction capacitance, and ϕ_o is the flux quantum. In the limit $\beta_c \ll 1$, the I-V characteristic is then described[8] by

$$V = R(I^2 - I_c^2)^{1/2} \quad . \tag{2}$$

The temperature fluctuations are assumed to generate fluctuations in $I_c(T)$, provided that $dI_c/dT \neq 0$. If the junction is biased with a current $I > I_c$, the critical current fluctuations will induce voltage

fluctuations whose power spectrum is given by replacing the coupling

terms $\bar{V}\beta$ in Eq. (1) by $(dI_c/dT)(\partial V/\partial I_c)_I$:

$$S_V(f) = \frac{(dI_c/dT)^2(\partial V/\partial I_c)_I^2 \, k_B T^2}{C_V[3 + 2\ln(\ell_1/\ell_2)]f} \quad . \tag{3}$$

From Eq. (2), $(\partial V/\partial I_c)_I$ is given by

$$\left(\frac{\partial V}{\partial I_c}\right)_I = \frac{-R}{[(I/I_c)^2 - 1]^{1/2}} \quad . \tag{4}$$

In deriving Eq. (3) we have assumed that at any instant in time the

temperature of the junction is uniform. This assumption is valid for

frequencies below $D/4\pi L^2$, where L is the largest dimension of the

junction. Using $D \sim 10 \ cm^2sec^{-1}$ and $L \sim 200 \ \mu m$ we find $D/4\pi L^2 \sim 2$ kHz,

a frequency much higher than the frequencies measured in the experiment.

There is some uncertainty whether or not the entire volume of the tunnel

junction contributes to C_V. Temperature fluctuations at a given point

in the superconducting film generate fluctuations in the energy gap, Δ,

over distances up to the Ginzburg-Landau coherence length, ξ. The

critical current is related to the values of the gap, Δ_s, at the

surfaces of the films adjacent to the tunnel barrier. As a result,

fluctuations in Δ that occur at distances greater than ξ from the barrier

are not expected to affect Δ_s or I_c. We shall assume, therefore, that

if ξ is less than the thickness of the superconducting film then the

"effective" fluctuating volume is given by the product of the junction

area with the sum of the coherence lengths rather than with the total

thickness of the junction. Accordingly, we shall use for C_V the

expression

$$C_V = \ell_1 \ell_2 (c_1 \xi_1 + c_2 \xi_2) , \tag{5}$$

where c_1 and c_2 and ξ_1 and ξ_2 are the specific heats and coherence lengths of the two superconductors. We have neglected the contribution of the barrier to the heat capacity.

III. EXPERIMENTAL DETAILS

Our Josephson tunnel junctions were resistively shunted by means
of either a disk of copper under the intersection of the two superconducting
strips, or by a diagonal strip of copper connecting the two strips near
their intersection. After the shunts had been evaporated onto a glass
substrate, niobium strips 150 μm wide and approximately 0.2 μm thick
were sputtered onto the substrate using a Sloan S-300 Sputtergun. The
niobium strips were thermally oxidized, and lead or tin cross strips
of similar dimensions were then evaporated. In the case of junctions
with diagonal shunts, the area near the junction was coated with an
insulating layer and a lead disk evaporated over the junction and the
shunt. This superconducting ground plane reduced the inductance of the
superconducting strips and the shunt to a negligible level. The shunt
resistance was typically 10 mΩ, and the critical currents at 4.2K were
in the range 200 μA to 5 mA. Assuming a junction capacitance of 500 pF,
we find that the corresponding range of β_c was 0.03 to 0.75. Each slide
was mounted in thermal contact with a copper block suspended in a vacuum
can. A carbon resistance thermometer was attached to the reverse side
of the block. At liquid helium temperatures, the thermal time constant
of the block was about 15 min, so that effects due to fluctuations in the
temperature of the helium bath were minimized. For measurements at
temperatures below 4.2 K, the temperature of the helium bath was regulated
with a manostat to within ± 100 μK.

The measurement configuration is shown in Fig. 1. Two tunnel
junctions of comparable critical current and resistance were connected
in series with a superconducting coil mounted inside a dc SQUID[10] and a
standard resistor, $R_v (\gtrsim R)$, of resistance 0.01 to 0.1 Ω. Niobium leads
50 μm in diameter were spot welded to 2×2 mm brass tabs that were then
soldered to the lead or tin films with indium-bismuth solder. The
entire measuring circuit, including the SQUID, was surrounded by a long
lead tube that greatly attenuated fluctuations in the external magnetic
field. The ambient magnetic field was reduced to below 10^{-6} T by a double
mu-metal can surrounding the cryostat. We obtained fluctuation spectra
in the following manner. The temperature of the copper block was allowed
to stabilize at the desired temperature. With the feedback loop of the
dc SQUID unlocked, the bias current I (see Fig. 1) through one of the
junctions was slowly increased. The current was supplied by a mercury
battery, and in a separate experiment had been found to have negligible
noise and drift. When I exceeded the junction critical current a current
I_v was induced in the measurement circuit; the output of the SQUID
oscillated as I was further increased. When the bias current had been
set at the desired value ($> I_c$) the SQUID was switched into its flux-
locked mode in which small changes of current in the coil could be detected.
Thus the zero of the SQUID voltmeter was effectively dc offset so that the
voltmeter measured only fluctuations in the voltage across the tunnel
junction. This offset was achieved with no loss in the stability of the
voltmeter. The bias current was always kept below the value at which
I_v exceeded the critical current of the second junction. Thus the only
resistances in the cricuit were R_v and the resistance of the tunnel junction.

At the frequencies of interest (< 100 Hz) the reactances of the superconducting coil (< 1 µH) and of the stray inductances were negligible compared with R_v.

Since the junction resistance and R_v were often comparable, the the voltage fluctuations developed across the junction were less than the value that would be measured by a voltmeter with an infinite input resistance. A straightforward calculation shows that the shunting effect of R_v reduces $(\partial V/\partial I_c)_I$ to a value

$$\left(\frac{\partial V}{\partial I_c}\right)^{(s)}_I = R_v \left(\frac{\partial I_v}{\partial I_c}\right)_I = \frac{-R}{[(I/I_c)^2 - 1 + (R/R_v)^2]^{1/2}} \quad . \quad (6)$$

Equation (6) is used in Eq. (3) in subsequent calculations of $S_v(f)$.

When the SQUID was in a flux-locked loop, the current resolution in the superconducting coil was about 10^{-11} A $Hz^{-1/2}$ at 1 Hz. Over the frequency range 10^{-2} to 10^2 Hz, the resolution of the experiment was limited by the white current noise generated by R_v and the tunnel junction, of order 10^{-10} A $Hz^{-1/2}$ at 4.2 K. The current noise corresponds to a voltage resolution of about 10^{-12} V $Hz^{-1/2}$ for a circuit resistance of order 10^{-2} Ω. Below 10^{-2} Hz, 1/f noise from the SQUID became significant. The power spectrum, $S_v(f)$, of the voltage fluctuations was obtained by digitizing the signal from the output of the flux-locked SQUID and taking a Fast Fourier Transform of the digitized signal with a PDP-11/20 computer. The transform was squared and stored, and the process repeated, typically 30 times, to obtain an averaged power spectrum.[5]

IV. EXPERIMENTAL RESULTS

In Fig. 2 we plot the power spectra of the measured low frequency

noise in a Nb-NbOx-Pb tunnel junction at 4.2K with I_c = 3.4 mA,

R = 5×10^{-3} Ω, R_v = 1.5×10^{-2} Ω, and dI_c/dT = 0.8 mA K^{-1}. The spectra

are shown for three values of bias current: I = 3.5 mA, 4.0 mA, and

7.0 mA. The power spectra were reproducible to within about a factor

of two under a given set of experimental conditions. The power spectra at

low frequencies vary as $f^{-\alpha}$, where 0.9 < α < 1.15. At the higher

frequencies (> 1 Hz for I = 7.0 mA, and > 5 Hz for I = 4.0 mA), the

spectra flatten with increasing frequency as the contribution of the

white noise becomes significant: Note that the magnitude of the power

spectra _decreases_ as the bias current _increases_. This current dependence

is in marked contrast to that observed for thin metal films, where

$S_v(f)$ is proportional to I^2. The dashed lines in Fig. 2 are calculated

from Eqs. (3), (5), and (6) using ξ_{Pb} = 80 nm, ξ_{Nb} = 50 nm, c_{Pb} = 8×10^{-3} JK^{-1}

cm^{-3}, and c_{Nb} = 2.5×10^{-3} JK^{-1} cm^{-3}.[9] In each case, the theoretical line

is within a factor of two of the corresponding experimental curve in the

frequency range where the measured curves vary approximately as 1/f.

The ratios of the magnitudes of the three theoretical curves for I = 7.0 mA,

4.0 mA, and 3.5 mA, 1:6.8:19.6 are in excellent agreement with the ratios

of the magnitudes of the experimental curves, 1:6.8:20 at 0.1 Hz.

The fact that $S_v(f)$ at a given frequency decreases with increasing

bias current is very strong evidence that the measured 1/f voltage noise

arises from fluctuations in the critical current. This current dependence

arises from the denominator of the term $(\partial V/\partial I_c)_I$ in Eq. (3): As the

bias current is increased, the junction resistance becomes progressively

more ohmic and less sensitive to fluctuations in critical current.

If the noise were generated by a fluctuating resistance $S_V(f)$ would

increase with increasing bias current. Alternatively, if the noise were

inherent in the bias current (a possibility excluded in any case by

separate measurements) $S_V(f)$ would also increase as the current was

increased.

Approximately fifteen Nb-NbOx-Pb or Nb-NbOx-Sn junctions were studied,

in one case down to a frequency of 5×10^{-3} Hz. The spectra shown in

Fig. 2 are representative of the spectra observed. In all cases the low

frequency power spectrum scaled approximately as 1/f with a magnitude

that was within a factor of 5 of the prediction of Eq. (3). In particular,

the decrease of $S_V(f)$ with increasing bias current was always observed.

It should be noted that in calculating the theoretical power

spectra of Fig. 2 the logarithmic term in the denominator of Eq. (3) was

zero because $\ell_1 = \ell_2$ for our junctions. The vanishing of the logarithmic

term indicates a deficiency of the semi-empirical model: Since f_1 and f_2

are the lower and upper limits of the 1/f region, f_1 and f_2 clearly

cannot be equal, and therefore cannot be given by $D/4\pi\ell_1^2$ and $D/4\pi\ell_2^2$.

Because the observed ratio f_2/f_1 is at least 10^3, the normalization

constant $[3+\ell n(f_2/f_1)]$ must be at least 10. If one uses this value in

Eq. (3), the calculated spectra in Fig. 2 will be reduced by about a

factor of 3. However, since the theoretical predictions in Fig. 2 tend

to lie somewhat above the data, this reduction would still maintain a

reasonable agreement between theory and experiment. This deficiency

can only be removed by a more microscopic understanding of the noise,

and for the moment we shall use Eq. (3) in calculating the power spectra.

We have investigated the temperature dependence of $S_V(f)$ by lowering

the sample temperature. In the case of Nb-NbOx-Pb junctions, the noise

decreased by a factor of between 2 and 5 when the temperature was lowered

from 4.2K to 1.5K. This rather weak temperature dependence can be readily

understood from Eq. (3). The terms $T^2(dI_c/dT)^2$ decreased by about two

orders of magnitude (using measured values of dI_c/dT) while C_V ($\propto T^3$)

decreased by a factor of about 20 as the temperature was decreased from

4.2K to 1.5K. Thus $S_V(f)$ is expected to decrease by roughly a factor

of 5. The rather wide variation in the observed temperature dependence

from junction to junction was due to variations in the value of dT_c/dT

at a given temperature.

Because dI_c/dT varied relatively slowly with temperature, it was

difficult to convincingly establish that $S_V(f)$ scaled as $(dI_c/dT)^2$ from

the temperature dependence of the power spectra for the Nb-NbOx-Pb

junctions. Fortunately, the critical current of one Nb-NbOx-Sn junction

had a highly anomalous temperature dependence that enabled us to clearly

show that $S_V(f)$ varied as $(dI_c/dT)^2$. The variation of I_c with temperature

for this junction is shown in Fig. 3. As the temperature was lowered from

2.6K, the critical current increased to a maximum near 2.0K, decreased

down to about 1.7K, and finally increased again. This behavior was

reproducible after the junction had been warmed to room temperature and

recooled three times. We have no detailed explanation for the effect,

but can speculate on a possible origin. After the niobium was sputtered

onto the substrate, the sputtering current was not switched off abruptly,

but decreased to zero over a period of several seconds. As a result the

last few atomic layers of niobium were deposited slowly, and may not have

been superconducting above 1K. Thus the junction contained a normal layer

(N) between the superconducting niobium film (S) and the insulating

barrier (I). SNIS junctions with this configuration have been analysed

theoretically by McMillan.[12] He finds that the amplitude of the order

parameter at the outer normal surface of a SN layer oscillates with

temperature, implying that the Josephson critical current of a SNIS

junction also oscillates with temperature. It is therefore possible that

we have observed the effect predicted by McMillan. R. C. Dynes[13] has

observed a similar effect in a Pb-PbOx-Ag-Pb junction.

Although the origin of the anomalous temperature dependence is

speculative, the effect is extremely useful for studying the dependence

of $S_V(f)$ on (dI_c/dT). A relatively small variation in temperature can

change dI_c/dT by a large factor while producing only a small change in

T^2/C_V. In Fig. 4 we plot $S_V(f)$ for this junction at 1.8K, where $dI_c/dT =$

2.1 mA K^{-1}, and at 2.0K, where $dI_c/dT = 0.6$ mA K^{-1}. In both cases,

$I/I_c = 1.2$. The average ratio of the magnitudes of the power spectra

at 1.8K and 2.0K (the slopes differ slightly) is 14.7, while the expected

ratio of $(dI_c/dT)/T$ at the two temperatures is about 14. The dashed

lines are calculated from Eq. (3), using $\xi_{Nb} = 50$ nm, $t_{Sn} = 150$ nm,

$c_{Nb}(2.0K) = 1.3\times10^{-4}$ JK^{-1} cm^{-3}, $c_{Nb}(1.8K) = 9\times10^{-5}$ JK^{-1} cm^{-3},

$c_{Sn}(2.0K) = 3.7\times10^{-4}$ JK^{-1} cm^{-3}, and $c_{Sn}(1.8K) = 2.6\times10^{-4}$ JK^{-1} cm^{-3},

$R = 0.013\Omega$, $R_V = 0.1$ Ω, $I_c = 530$ μA, and $I/I_c = 1.2$. Since the coherence

length for tin (0.24 μm) is larger than the thickness of the tin film,

t_{Sn}, we have used t_{Sn} rather than ξ_{Sn} in the calculation of C_V. The

magnitudes of the calculated power spectra are in excellent agreement with

the measured power spectra. These results clearly demonstrate that

$S_V(f)$ is proportional to $(dI_c/dT)^2$.

Finally, we measured the power spectra of junctions biased at

currents of 10 mA or higher. We found that at these relatively high

levels of power dissipation (> 1 μW) the slope of the power spectra was

steeper than that shown in Figs. 2 and 4. The steeper slope indicated

that the power dissipation was sufficiently high to cause a significant

drift in the temperature of the junction and the copper block. (In our

method of data analysis a function that increases linearly with time has

a power spectrum proportional to f^{-2}.) In addition, a few power spectra

exhibited structure that we tentatively ascribed to thermal feedback

in the junction. We were unable to obtain any useful quantitative

results from junctions at high bias currents.

V. CONCLUSIONS

The scaling of $S_V(f)$ with $[(\partial V/\partial I_c)_I]^2$ and $(dI_c/dT)^2$ provides strong evidence that the 1/f noise observed in shunted Josephson tunnel junctions arises from equilibrium temperature fluctuations in the junction. The magnitudes of the observed power spectra are generally within a factor of 5 of the predictions of Eq. (3). As pointed out earlier, the geometrical factor $[3 + 2\ln(\ell_1/\ell_2)]$ is unlikely to be correct. In addition, we cannot determine experimentally whether or not the heat capacity C_V used in Eq. (3) corresponds precisely to a thickness given by the sum of the coherence lengths of the two superconductors. A study of the noise in junctions with a wide range of film thickness should resolve this question. Despite these difficulties, we now have an experimentally verified model that enables us to make reasonably accurate predictions of the 1/f noise in devices involving Josephson tunnel junctions. One may reduce the 1/f noise by minimizing the value of dI_c/dT without affecting the sensitivity of (for example) a SQUID to magnetic fields.

It would obviously be of interest to extend the measurements to other weak links such as the Anderson-Dayem bridge.[14] In this junction, the "effective" volume is of submicron dimensions, and Eq. (3) predicts that the 1/f noise should be much higher than that of a tunnel junction at the same temperature and with comparable values of dI_c/dT and $(\partial V/\partial I_c)_I$.

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Fig. 1. Configuration used for measuring 1/f noise in a shunted Josephson

tunnel junction.

Fig. 2. Power spectra of the voltage fluctuation of a Nb-NbOx-Pb junction

for three values of bias current I. The error bar indicates

the reproducibility of the experimental data.

Fig. 3. Anomalous temperature dependence of the critical current of a

Nb-NbOx-Sn junction.

Fig. 4. Power spectra of the voltage fluctuations of the Nb-NbOx-Sn

tunnel junction for which I_c versus temperature is plotted in

Fig. 3.