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Low Frequency Noise in Josephson Junctions*

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We have measured the low-frequency power spectrum of voltage fluctuations in shunted Josephson tunnel junctions biased with a constant current I greater than the junction critical current I_c. We find that the frequency dependence of the power spectrum is very nearly 1/f and that the amplitude of the spectrum is quantitatively predicted by a suitable modification of the semi-empirical formula of Clarke and Voss.[1]

Our samples consisted of Nb-NbO_x-Pb Josephson tunnel junctions deposited on glass slides. In order to avoid hysteresis in the current-voltage characteristic, the junctions were shunted to a resistance of approximately 7mΩ by a strip of copper predeposited on the substrate. Thus for a critical current of 1mA, the hysteresis parameter[2] $\beta_c=2\pi I_c R^2 C/\phi_o$ was about 0.2. (C is the junction capacitance, about 200pF, and ϕ_o is the flux quantum.) The glass slide was mounted in thermal contact with a copper block suspended in a vacuum can surrounded by liquid helium. The thermal time-constant of the block was chosen to be approximately 15 minutes, so that the effects of temperature fluctuations and drifts in the helium bath were small at the lowest frequencies measured (5×10^{-3}Hz). Electrical connections to the junctions were made with 50μ insulated Nb leads.

A carefully stabilized and filtered current greater than I_c biased the sample junction at a non-zero voltage. Voltage leads from the sample were connected in series with a standard resistor R_S ($\sim10^{-2}\Omega$) and a superconducting coil coupled to a SQUID magnetometer. The voltage resolution of our system was typically $10^{-12}V/\sqrt{Hz}$ at frequencies above 1 Hz; below 1Hz, the noise power spectrum of the voltmeter was approximately 1/f. Fluctuations about the mean voltage across the tunnel junction were detected by the SQUID in a feedback mode, amplified by room temperature electronics, and analyzed by a PDP-11 computer to obtain the power spectra. Data points for the noise power spectrum $S_V(f)$ are plotted against frequency in Fig. 1 for three values of bias current I. The junction critical current of this sample was 3.4mA at the temperature of the experiment, 4.2K, and the measured value of dI_c/dT was 0.8mA/K. The junction resistance R_J and standard resistance R_S were 5mΩ and 10mΩ respectively. There are two important features shown in Fig. 1. First, at low frequencies the spectra obey the power law $f^{-\alpha}$, where $0.9<\alpha<1.15$. Second, at any given frequency, the magnitude of the spectra <u>decreases</u> as the bias current I is <u>increased</u>.

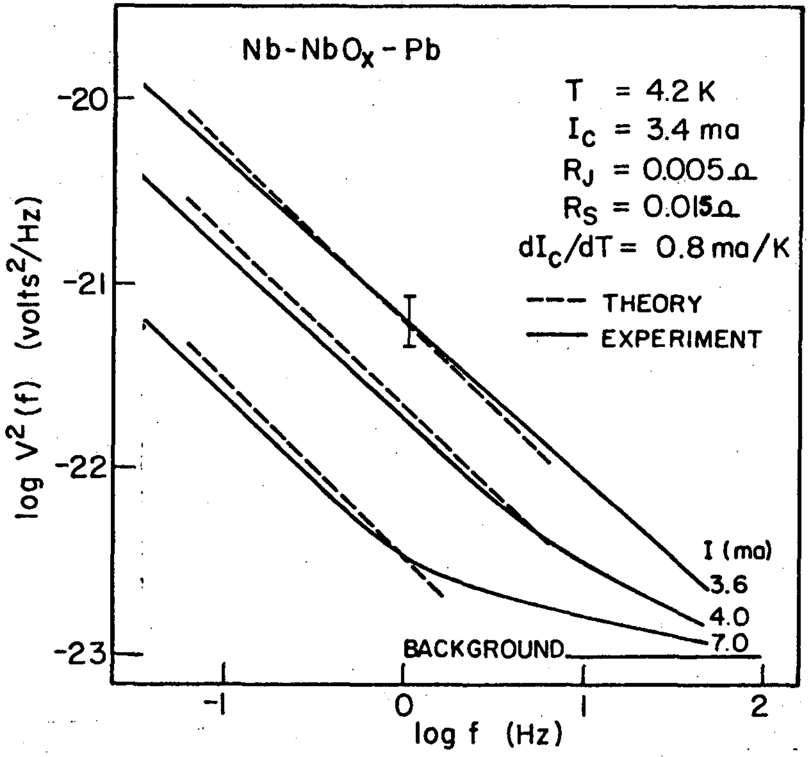

Fig. 1. Noise spectra for three values of bias current.

We believe that the observed 1/f noise arises from equilibrium temperature fluctuations in the junctions themselves. These fluctuations modulate the critical current, which in turn modulates the voltage across the junction at constant current bias. Hence, according to this interpretation, the voltage fluctuations are predicted to be given by $\delta V=(dI_c/dT)(\partial V/\partial I_c)_I\delta T$. For an ideal shunted junctions with zero capacitance ($\beta_c=0$), the Stewart-McCumber[2] model relates the voltage V across a junction to the current flowing through it via the equation $V=R(I^2-I_c{}^2)^{1/2}$ for $I\geq I_c$. Thus, we find

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

which decreases as I increases, thus explaining qualitatively the decrease of the noise spectrum with increasing bias current.

The semi-empirical model of Clarke and Voss[1] may be modified to account for the voltage fluctuations in a Josephson junction. We find

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

The lengths ℓ_1 and ℓ_2 are the widths of the niobium and lead films: since $\ell_1\approx\ell_1$, $\ln(\ell_1/\ell_2)$ may be neglected. C_V is the heat capacity of the "active volume" of the junction which we take to be the area of the junction times the sum of the Ginzburg-Landau coherence lengths in the lead and niobium. (Fluctuations in temperature,and therefore in pair condensation amplitude, that occur at a distance from the barrier greater than a coherence length are not expected to affect the critical current.) If we combine Eqs. (1) and (2) and insert the measured values of R, I, I_c, (dI_c/dT), T, and the values of C_V calculated from measured values in the literature, we can estimate S(f). The resultant spectra for the three bias currents used are shown as dashed lines in Fig. 1. The agreement between the measured spectra and the predictions of the semi-empirical model is excellent. In particular, the spectra scale with bias current in the predicted manner.

We encountered one sample junction which exhibited an anomalous temperature dependence of the critical current. As the temperature was lowered below 2.5K, I_c rose to a maximum at 2.0K and then decreased as the temperature was further reduced. Thus, at the turning point, the coupling term (dI_c/dT) vanished. When the temperature of the junction was near this turning point, the observed 1/f noise decreased to a value below the noise of the voltmeter. This result demonstrates that junctions with a sufficiently small temperature dependence of critical current have very little 1/f noise.

References and Footnotes

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