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NOISE VOLTAGE IN JOSEPHSON JUNCTIONS

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The theoretical prediction of voltage across Josephson junctions due to thermal noise currents is shown to be in reasonable agreement with experiments in which noise currents of variable "temperature" were produced by the radiation of a gas discharge.

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FOREWORD

This report is published by The Aerospace Corporation, El Segundo, California, under Air Force Contract F04701-71-C-0172.

This report, which documents research carried out from January through June 1969, was submitted on 7 October 1971 to Lt William E. Belote, SYAE, for review and approval

Approved

A. H. Silver, Director
Electronics Research Laboratory

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

W. E. Belote, 1st Lt, USAF
Project Officer

NOISE VOLTAGE IN JOSEPHSON JUNCTIONS

Recently work appeared on theoretically expected I-V characteristics of current driven Josephson junctions when subjected to thermal noise. While earlier predictions [1,2] were restricted to the limit of junctions with circuit time constant $\tau \ll \omega_J^{-1}$, the inverse of the so-called Josephson plasma frequency, which could be treated with methods developed for Brownian motion, later work [3] employing numerical integration of the equation of motion for the phase difference between superconductors produced results applicable to the more easily realizable case of $\tau \gtrsim \omega_J^{-1}$. The earlier results have been experimentally tested for both thin film junctions [4] and constricted film weak links [5]. In both cases the critical current was lowered by operating arbitrarily close to the transition temperature. Agreement of the resulting I-V characteristics with theoretical predictions was accomplished by adjusting the critical current and effective bath temperature [4] or the critical current [5]. We observed I-V characteristics of Nb-Nb point contacts at 4.2°K situated in an E-band wave guide and illuminated with the radiation of a gas-discharge tube ($f_{min} \approx 60$ GHz) which over a considerable voltage region were in agreement with predictions for $\tau \gtrsim \omega_J^{-1}$. The frequency spectrum of the induced noise currents was sufficiently high to be considered "thermal" at least for the lower voltage range investigated ($eV/\hbar < f_{min}$). The application of external noise currents allows one to investigate the "temperature" dependence conveniently since the relative amplitude can be varied without changing junction parameters. Furthermore, the noise amplitude can be made large enough to operate on junctions of sufficiently high critical current to minimize the effect of other unavoidable noise sources.

Recorder plots of I-V characteristics of a point contact are shown in fig. 1 by solid lines for various settings of the attenuator with which the amount of radiation from the noise source was varied. Also shown are theoretical results taken from refs. [6,3]. The two parameters controlling the theoretical curves are: 1) $\Omega = \tau\omega_J$ with $\tau = RC$ and $\omega_J^2 = 2eI_c/\hbar C$ where I_c

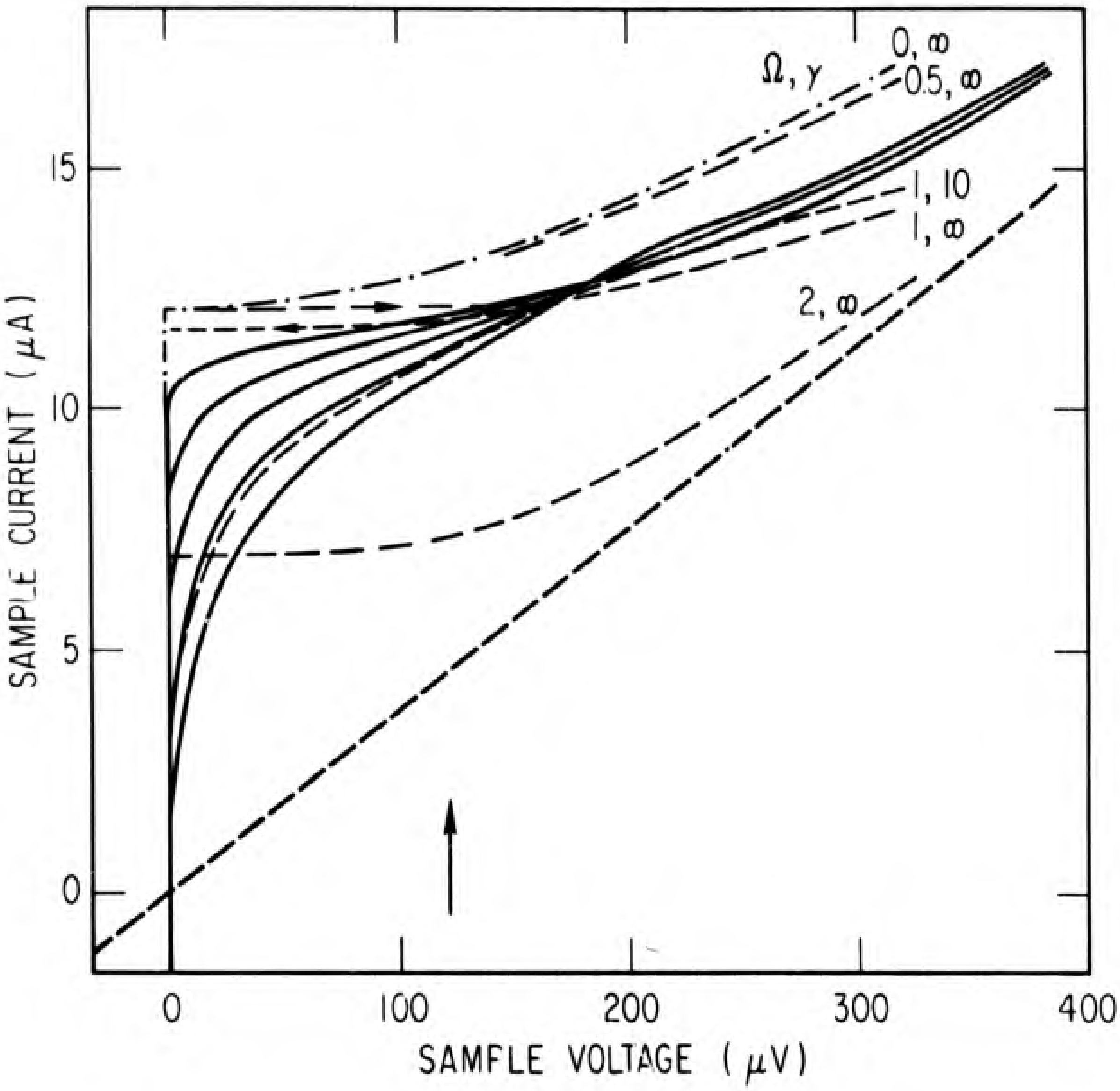

Fig. 1. Recorder plots of I-V characteristics (solid lines). The attenuator setting is ∞, 7, 4, 2 and 0 dB going from left to right, respectively. The arrow corresponds to a Josephson frequency of 60 GHz, the minimum frequency of the noise source. The straight line has been chosen parallel to the characteristic at large (> 1 mV) positive and negative voltages. Superimposed are theoretically expected characteristics for various values of the damping and temperature parameter.

is the critical current, R and C the junction resistance and capacitance, respectively, and 2) $\gamma = \hbar I_c/ekT$, the ratio of pair binding energy and thermal energy. For our point contact Ω was determined from the shape of the noise-free characteristic near 1.5°K by comparing with the curves $\Omega = 0, 0.5, 1$ and $\gamma = \infty$. The value found for Ω is $\lesssim 1$. As shown by the horizontal arrows in fig. 1 hysteresis was observed as previously described [6,7]. The experimental curve in this range was very close to the theoretical curve shown. Little amibguity was left in choosing the proper scale for the theoretical curves, since I_c could be determined with reasonable accuracy at 1.5°K and the current value near 300 μV depends critically on Ω. The remaining deviation in fig. 1 of the theoretical curves from the experimental ones near 300 μV thus cannot be removed by changing the voltage scale, but reflects the fact that actually our $\Omega < 1$.

We were not able to determine the parameter γ absolutely since the coupling efficiency of the radiation into the contact was not known. However, the change of junction voltage at a constant battery current ($\approx 0.8\ I_c$) with input power ($\approx \gamma^{-1}$) follows the predicted dependence (not shown). The voltage change agrees quite well with the calculations for $\Omega = 0$ when $V < 30$ μV, but as evident from fig. 1 the more recent prediction extends the agreement to $V \sim 100$ μV. At larger voltages the noise currents cannot be considered thermal and deviation is expected.

Our experimental characteristics show the noise-including curves to cross the noise-free curve more abruptly than expected by theory. For all investigated samples this transition occurs in a voltage range where $\overline{V} = \hbar\omega/2e$ is commensurate with the radiation spectrum. The cross-over region is rather reminiscent of the step induced in the I-V characteristic by single frequency excitation [e.g.,8]. The abruptness of our curve may reflect a finite width to the spectrum of our noise source. It is also possible that resonance effects between exciting and Josephson frequency affect the characteristic, since with $\tau = 10^{-12}$ sec of our junction such phenomena cannot be expected to be completely damped out.[1] Extension of the theory to include resonance effects in Josephson junctions would be of interest.

[1] The response time is estimated from $\Omega \approx 1$, the function resistance at large voltage and the critical current. Using the measured resistance of 27 ohm we find $C \approx 0.03$ pF.

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