DEPENDENCE OF THE VOLTAGE NOISE ON SAMPLE QUALITY IN HIGH-T_C SUPERCONDUCTING $Y_1Ba_2Cu_3O_7$ THIN FILMS

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***Abstract**: In this paper, the voltage noise (S_v) in $Y_1Ba_2Cu_3O_7$ (YBCO) thin films prepared by dc magnetron sputtering technique on $SrTiO_3$ substrate and its dependence on various parameters such as temperature, bias current and frequency are discussed. The voltage noise characteristics shows an enhanced peak near transition temperature (T_c) except for best quality samples with better surface morphology, lesser number of grain boundaries and having high critical current density (J_c). The calculated value of Hooge's parameter using the carrier density $N_c=10^{21}/ cm^3$ for the thin film was 0.004 at 300K. To understand the effect of sample quality on voltage noise, measurements were performed on $Y_1Ba_2Cu_3O_7$ thin films of different characteristics.*

***Keywords:** Hooge's parameter, percolation noise, spectral noise density, YBCO thin film.*

1. INTRODUCTION

Voltage noise in high-T_c superconductors determines the ultimate sensitivity of superconducting devices and it depend on the temperature, current and frequency. The voltage noise is found in metals, semiconductors, superconductors and even in devices like SQUIDs. The low frequency noise in superconducting materials is related to the critical current density, grain boundary weak links, phase. orientation and dynamics of vortices in an applied magnetic field [1-5]. The excess noise in YBCO is approaching zero in superconducting state and start rising sharply in the transition region [4]. The T_c-inhomogeneity may also lead to thermodynamic noise in superconductors [6]. For YBCO single crystal the 1/f noise power spectral densities are five orders of magnitude larger than clean metallic samples [7,8]. The strong 1/f noise in YBCO has been attributed to conduction along the one-dimensional Cu-O chains [9]. For low-T_c conventional superconductor, the 1/f noise is related to the dynamics of vortex and flux bundle pinning just below the superconducting transition [10-12]. For granular YBCO superconducting samples, the noise is associated with grain boundaries and percolation effects near superconducting transition. The highly anisotropic YBCO [13] superconducting thin films having different critical current density, phase and orientation has been chosen for the present study.

2. THEORETICAL MODELS

2.1. Thermal fluctuation model

The normalized voltage noise for thermal fluctuation model is given by

$$\frac{S_v}{V^2}=\frac{\beta^2 k_B T^2}{C_v[3+2\ln(\frac{l_1}{l_2})f]}$$

Where $\beta=(dR/dT)/R$ is the temperature coefficient of resistance. C_v is the heat capacity, K_B is the Boltzmann constant and $\{3+2\ \ln(l_1/l_2)\}$ is a geometrical parameter with length l_1 and width l_2 of the thin film sample respectively [14-17]. Low frequency conduction noise behavior in conventional superconductors is explained by thermal fluctuation model. The defects due to oxygen vacancies which may lead to fluctuations in local carrier density in the copper oxygen planes for $Y_1Ba_2Cu_3O_7$ can affect many of the superconducting parameters may leads to single sharp noise peak near the transition temperature [10]. This peak is usually analyzed in terms of the temperature fluctuation model [18].

2.2 Hooge's relation

Hooge's expression for voltage noise spectral density (S_v) for an ohmic sample is given by [19]

$$\frac{S_v}{v^2}=\frac{\gamma}{N_c f^{\alpha}}$$

where v is the dc voltage applied across the sample, γ is Hooge's parameter and is dimensionless constant. α is also a constant equal to unity and N_c is the total number of charge carriers in the sample which is proportional to the sample volume. γ value is about 10^{-1} to 10^{-3} for metals depending on the strength of lattice disorder. The spectral density of voltage noise is independent of temperature and is a power law at all frequencies.

2.3. Percolation noise model

This model [3,12,18] describes the temperature dependence of the resistance noise near superconducting transition showing a sharp rise. In the absence of applied magnetic field, the normalized noise is proportional to $R^{-k'/s}$, where R represents the macroscopic sample resistance and k' and s are critical exponents .and the ratio k'/s can be regarded as an index of the rise of normalized noise [25]. Here, a superconductor is represented as a resistance network whose element was grain boundary junctions. The resistance of the network as a whole is determined by a fraction of superconducting junction p, and resistance fluctuations by random switching of these junctions (p-noise). The number of switching junctions is assumed to be independent of temperature. The origin of noise may be the percolation process between grains in the film. The amplitude of the temperature dependence of p-noise depends on the degree of structural disorder in the sample [26].

3. EXPERIMENTAL

3.1 Experimental set-up

Figure 1 shows schematic of the experimental set-up used voltage-noise measurement in a high-T_c superconducting film [5]. For the measurement of low frequency voltage noise, the sample was mounted on a copper sample holder. Temperature of the sample was monitored with a silicon diode thermometer (D-T 470, Lakeshore USA), mounted on the sample holder close to thin film sample. A non-inductively wound manganin heater wire of 20Ω resistance was fixed at the center of the sample holder which was mounted inside a vacuum can was made of brass. The sample holder was connected to the liquid nitrogen bath with a weak thermal link made of stainless steel. The temperature of the sample could be varied by changing the current in the heater. The temperature of the sample was monitored and controlled with a cryogenic temperature controller (Lakeshore, USA, DTC-93C) within the accuracy of ± 0.05 K. Voltage noise was measured by standard four probe technique in the spectral range 0.5 to 100 Hz.

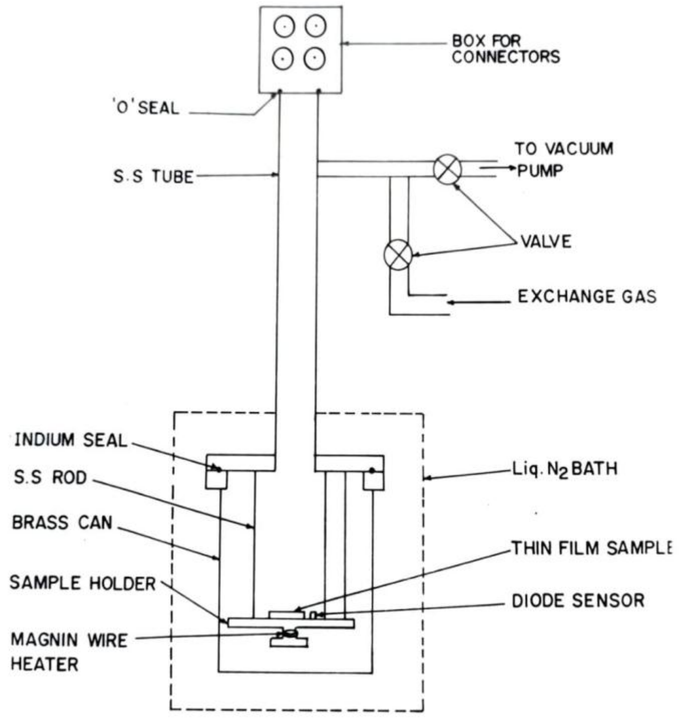

Figure 1. Schematic of the experimental set-up used voltage-noise measurement in a high-T_c superconducting film

A battery-generated dc-current was passed through the sample with a large ballast resistance R_b, in series to minimize the noise due to contacts. The voltage signal developed across the sample was ac-coupled to a low noise pre-amplifier (Stanford-USA, SR-560) which had a tunable band pass filter from dc to 1 MHz. Amplified voltage signal was then applied to a dynamic signal analyzer (Hewlett Packard, USA-35660) or to a lock in amplifier (SR-530) which measures the spectral density of noise (in 1 Hz bandwidth) of the input signal in the desired frequency range or at a fixed frequency respectively. Figure 2 shows the experimental set-up for low frequency noise measurement in a high-T_c superconducting thin film. The observed voltage noise is the sum of preamplifier noise and noise from the sample. The background noise of the system is measured without passing any current through the sample. By subtracting background noise from the measured noise, we can observe the excess noise corresponding to the sample. To avoid interference of signals from nearby sources the sample holder was surrounded with three layers of μ metal and the measurements were performed inside the rf-shielded room [23].

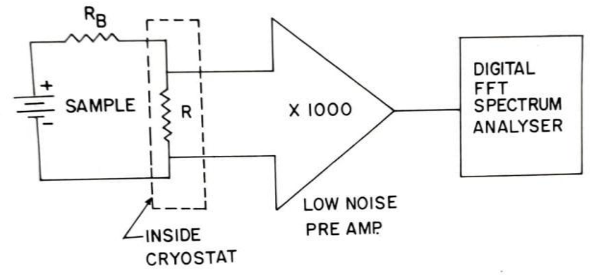

Figure 2 Experimental set-up for low frequency noise measurement in a high-T_c superconducting thin film

3.2 Sample preparation and characterization

The high-T_c $YBa_2Cu_3O_{7-x}$ thin films studied in the experiment were deposited onto (100) $SrTiO_3$ (10 x 10 mm^2) substrate by dc magnetron sputtering technique [20]. Target was stoichiometric $YBa_2Cu_3O_{7-x}$. Substrate was glued with silver paint to a heater block and heated to 700-750^{0}C during deposition. The sputtering gas pressure was maintained at 800mTorr during deposition. Immediately after deposition pure dry oxygen was introduced in the chamber up to 300 Torr. The substrate temperature was slowly decreased up to 475^{0}C and was kept at this temperature for one hour before removing the sample from the chamber. Thickness of samples was around 300 nm. The sample was patterned into a micro-bridge of dimension 50x50 μm^2 using standard photolithography followed by etching in saturated EDTA solution. In order to investigate the influence of orientation on the low frequency voltage noise behavior of the YBCO thin films, voltage noise was measured in two YBCO thin film samples of different phase and orientation. The samples were patterned into a micro-bridge of 50 x 50μm^2 dimension and low resistivity contacts were made on them. Prior to noise measurements, the electrical resistance and critical current density was measured using standard dc four-probe technique [21]. Figure 1 shows the temperature dependence of resistance measured for two YBCO thin film samples. The resistance was found to decrease with decreasing temperature until superconducting transition is approached. Sample 1 has T_c (R=0) values of 83K whereas the sample 2 was having a higher T_c (R=0) value of 90.5K. The J_c in ambient field at 77K for sample 1 and sample 2 were 5x10^4 and 1.5x10^{6}A/cm^2, respectively. The observed differences in the T_c and J_c values are attributed to the better crystalline quality of sample 2.

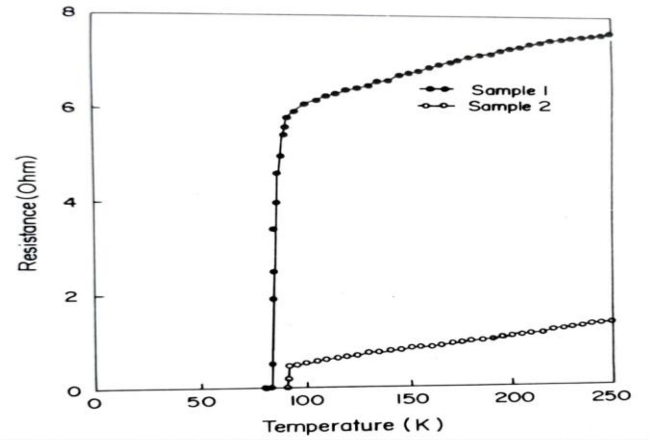

Figure 3. R-T curves for YBCO thin film micro-bridge sample 1 and sample 2

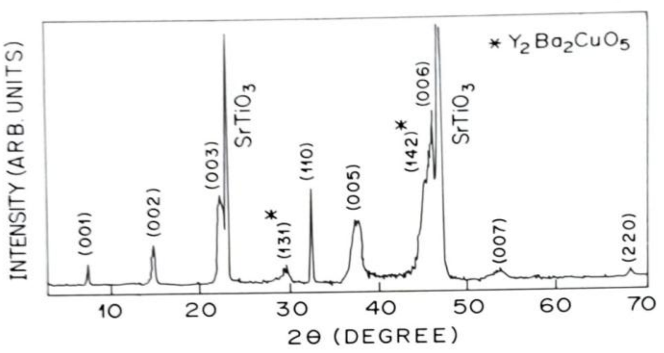

Figure 4. (a) X-ray Diffraction pattern of YBCO thin film sample 1

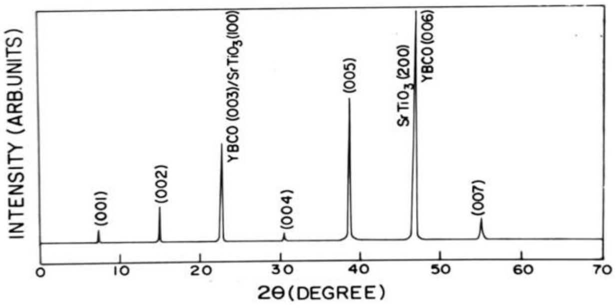

Figure 4. (b) X-ray Diffraction pattern of YBCO thin film sample 2.

Figure 4. (a) and (b) shows the XRD pattern of sample 1 and 2. θ-2θ scan shows reflection from (00l) $YBa_2Cu_3O_{7-x}$ crystallographic planes indicating the alignment of the YBCO c-axis perpendicular to the (100) plane of the substrate. We have seen some evidence of (131), (142)

peaks of Y_2BaCuO_5 and peak of $YBa_2Cu_3O_{7-x}$ (110) planes in sample 1, while for sample 2 no evidence of extraneous phases was found and the film was highly c-axis oriented. Table 1. shows the electrical properties of YBCO thin films.

Table 1. Superconducting properties of YBCO thin films.

Sample No.	R_{100K} (Ohm)	R_{300K} (Ohm)	T_c (R=0) (K)	Phase & Orientation	J_c (A/cm^2) (77K)
1	112.66	477	83	Mixed	$5x10^4$
2	7.95	23.62	90.5	Single	$1.5x10^6$

4. SPECTRAL DENSITY OF VOLTAGE NOISE

The voltage noise properties of the two YBCO thin film samples were investigated in the temperature range of 77-300K in the low frequency region (0.5-100Hz). Table 2 shows the noise properties of two YBCO thin film samples.

Table 2. The noise properties of two YBCO thin film samples

Sample No.	$\sqrt{S_v}$ nV√Hz (100K)	$\sqrt{S_v}$ nV√Hz (300K)
1	370	1200
2	17.7	39.5

4.1 As a function of biasing current

Figure 5 (a) and (b) shows the variation of spectral density of voltage noise (Sv) measured at 1Hz for sample 1 and 2 as a function of biasing current I_b, at 300K. The spectral density of voltage noise (Sv) was found to have I^2 dependence i.e., V^2 dependence [18].

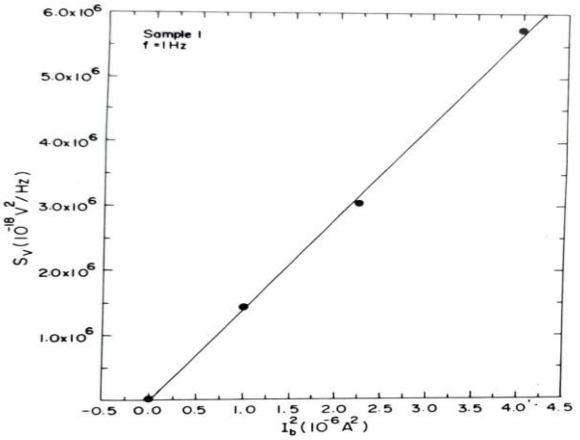

Figure 5 (a) Variation of spectral density of voltage noise S_v (1Hz, 300K) as a function of biasing current I_b for sample 1.

This confirms that the noise arises due to resistance fluctuations [2]. This result excludes the possibility that the noise generate at contact pads is dominant, if it was so, then S_v would have other than I^2 dependence [23].

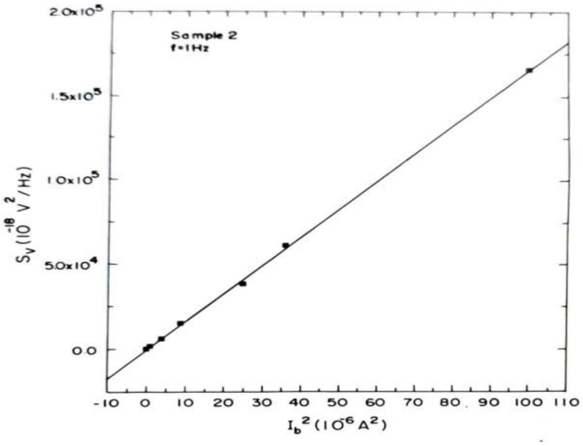

Figure 5 (b) Variation of spectral density of voltage noise S_v (1Hz, 300K) as a function of biasing current I_b for sample 2.

To check the contribution of noise generated at contacts to the measured noise, we have increased voltage and ballast resister both by a factor of 2 and 3 so that the ratio of sample resistance with ballast resistor is either doubled or tripled, but the voltage across sample remains constant. Magnitude of noise and the slope of noise spectrum were unaffected which suggests that noise generated due to contacts were negligible [23]. Moreover, I-V characteristic of the contacts was found to be linear for the strength of current employed during measurements.

4.2 As a function of frequency

Figure 6 shows the voltage noise spectrum (S_v –f) of sample 1 measured at three different temperatures 86.6K, 100K and 300K. From the figure it is clearly evident that Sv(f) has $1/f^{\alpha}$ dependence at low frequencies (<10Hz) for all the temperatures with α close to 1. Above this frequency the spectra are dominated by frequency independent noise (white noise) at low temperatures (86.6K and 100K) which are in the superconducting transition region. At higher temperature i.e. in the normal state the noise spectra shows $1/f^{\alpha}$ dependence throughout the measurement range of frequency [18,25].

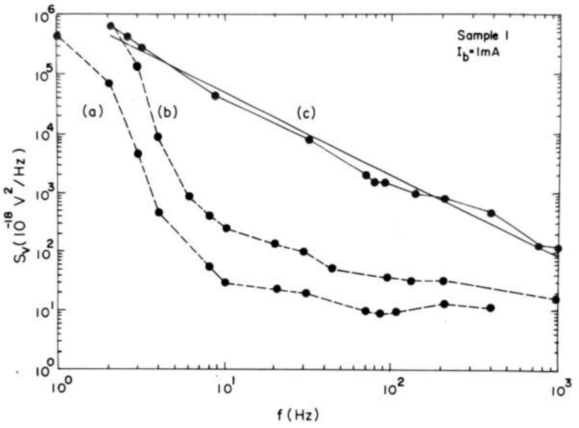

Figure 6. Voltage noise spectrum (S_v–f) of sample 1 measured at three different temperature (a) 86.6K, (b) 100K and (c) 300K.

4.3 As a function of temperature

Figure 7 (a) & (b) shows the temperature variation of S_v (1Hz) for samples 1 and 2, respectively, measured with a bias current of 1mA. It has been observed that the magnitude of S_v in the normal state for both samples shows a gradual decrease with the decrease in temperature. As the superconducting transition is reached the magnitude of S_v rises sharply and shows a noise peak. Below this temperature the magnitude of noise falls sharply [5]. Although, both samples showed a presence of noise peak in the transition region but for the sample 1 we have observed two peaks one near T_c (onset) and other one close to T_c (0) (i e at 83K). Magnitude of $\sqrt{S_v}$ in normal state for sample 2 is smaller by three orders of magnitude than that of sample 1.

The lower magnitude of noise peak in transition region for sample 2 is due to the fact that this YBCO thin film is of very good quality; highly c-axis oriented and has higher J_c value as compared with sample 1. The oriented nature of sample 2 is expected to give lower magnitude of noise, as there exists a large conduction anisotropy in the YBCO material. Also, in sample 2 the conduction is in the a-b plane which reduces the scattering of charge carriers. The larger noise peak observed for sample 1 is possibly due to the enhanced scattering caused due to crystal imperfections as well as randomly aligned grains. The noise near the T_c onset appears to be associated with the thermal fluctuation and with the fluctuation in the number of cooper pairs due to its short coherence length [2]. In the lower part of the transition region superconductor grains are at random locations results in random distribution of current density which naturally leads to percolation effects in this regime. The neighboring grains form superconducting islands via Josephson coupling and at lower temperature the percolation length of these islands is becoming larger. When the percolation length reaches the thickness of the film, a 3-D/2-D dimensional crossover occurs [25].

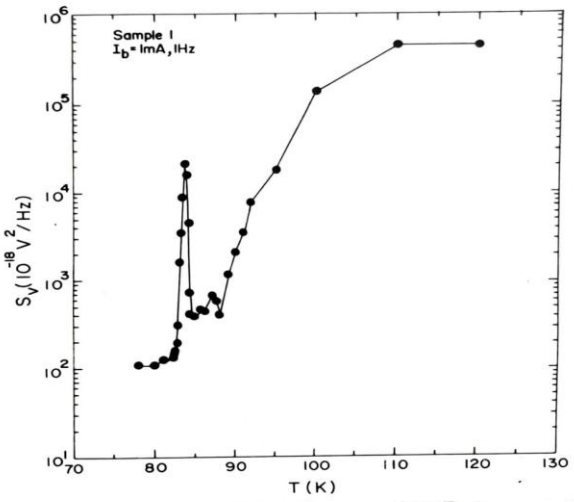

Figure 7(a) Temperature variation of S_v at 1Hz for sample 1 measured with a bias current of 1mA.

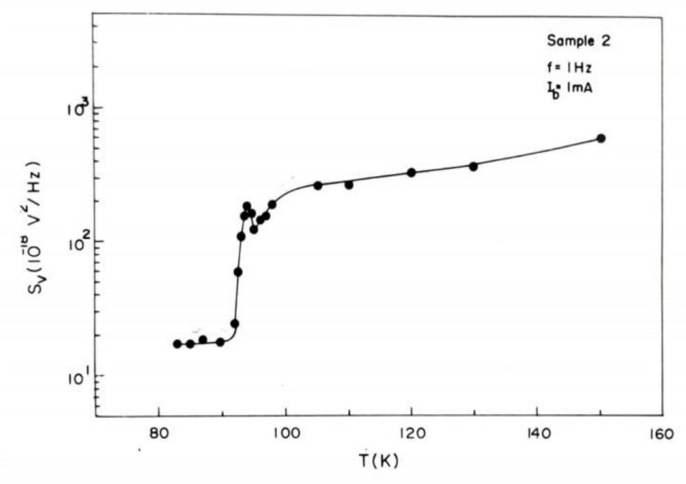

Figure 7(b) Temperature variation of S_v at 1Hz for sample 2 measured with a bias current of 1mA.

Near superconducting transition, the conductivity fluctuations arise due to the fluctuation in the mobility and density of the carriers [10]. At temperature < T_c (R=0), at low bias currents, a continuous superconducting path exist which suggests that vortex motion is the source for noise in this region [22]. It is due to thermally activated diffusive vortex motion and is enhanced by a strong Lorentz force due to the applied current [2,15,18]. The excess noise has been observed in granular and mixed orientation YBCO superconducting films as compared to high quality epitaxial c-axis oriented film [23]. The magnitude of spectral noise density in c-axis oriented films is about two orders less than mixed oriented films. In c-axis oriented films, transport occurs through a set of parallel layers consisting of CuO_2 planes (in a-b directions) and CuO chains (along the b direction). Oxygen depletion is known to create vacancies within the chains [9]. The one-dimensional chain leads to significant resistance fluctuations in the planes. Noise peak near transition temperature is more for sample 1, which has mixed orientation. Sample 1 has a larger electrical noise magnitude than sample 2, which is c-axis-oriented film. The improved noise performance of samples with large size grains is related to the presence of a smaller number of grain boundaries [23]. These grain boundary acts as Josephson weaklinks and contribute to the observed noise.

5. TEMPERATURE DEPENDENCE OF NORMALIZED NOISE

The normalized noise voltage spectral density was plotted for both samples Figure 8. shows the temperature dependence of normalized noise S_v/V^2 for YBCO thin film sample 2. Magnitude of S_v/V^2 remains constant in the normal state and shows a sharp rise by several orders of magnitude as the transition temperature is reached. The enhancement of S_v/V^2 in the superconducting transition region is close to five orders of magnitude [24].

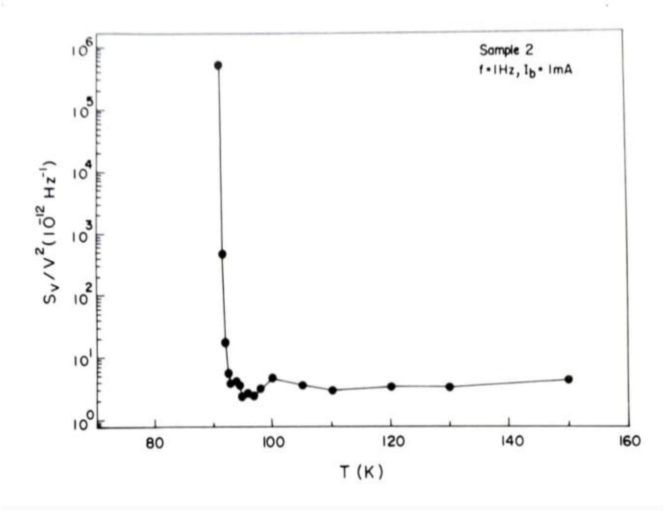

Figure 8. shows the temperature dependence of normalized noise S_v/V^2 for YBCO thin film sample 2.

6. HOOGE'S PARAMETER

The Hooge's parameter γ for two thin film samples are calculated using the carrier density $N_c=10^{21}/\ cm^3$ at room temperature and experimentally observed value of S_v/V^2. The numerical value of Hooge's parameter γ for the films is comparable to that of metals [5]. The lowest value of γ measured at 300K was 0.004 in YBCO thin film deposited on $SrTiO_3$ by dc magnetron sputtering technique (sample 1). It was found that the value of γ for sample 1 is lower than the single crystal value by a factor of 100. Table 3 shows the Hooge's parameters for two YBCO thin film samples

Table 3. The Hooge's parameters for the two YBCO thin film samples

Sample No.	γ (100K)	γ (120K)	γ (300K)
1	$2.35x10^{-2}$	$2.34x10^{-1}$	$4.21x10^{-3}$
2	$2.2x10^{-1}$	$1.5x10^{-1}$	$5.6x10^{-2}$

7.RESISTANCE DEPENDENCE OF NORMALIZED NOISE

Figure **9** shows normalized noise (S_v/V^2) versus resistance (R) on a log-log scale at biasing current 1 mA for YBCO thin film sample 2. The high value of slope (k= –3) for sample 2, is probably the result of superconducting islands whose thickness is just a little less than that of the film so that it is approaching the 3-D model for the p noise [3,4,18]. This result shows that the film is of high quality.

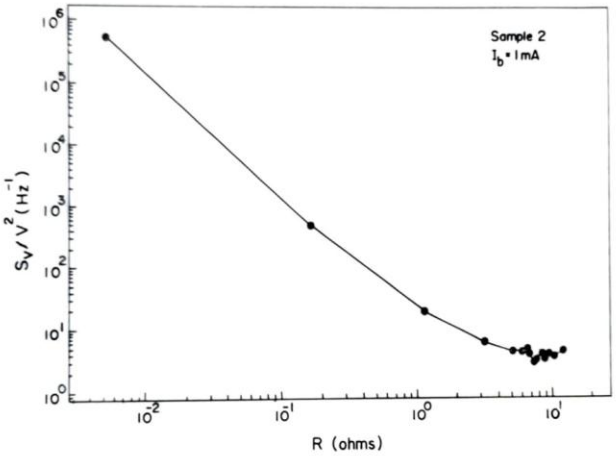

Figure 9. S_v/V^2 versus resistance R on a log-log scale at biasing current 1 mA for sample 2.

8. CONCLUSION

We have studied the voltage noise both in normal and superconducting state of YBCO thin films. The dependence of low frequency excess noise power (S_v) on current confirms that the noise arises due to resistance fluctuation. At superconducting transition temperature, the magnitude of spectral density of voltage noise $S_{v,}$ rises sharply and show a noise peak. Below this temperature the magnitude of noise fall sharply. Amplitude of the noise peak near superconducting transition temperature also found to decrease gradually as sample quality improves and disappears for best quality samples. The low noise level was due to the best lattice matching between the substrate and lesser number of grain boundaries. The in-situ annealed c-axis oriented films has γ values ~ 0.004 at T=300K. The magnitude of normalized noise S_v/V^2 remains constant in the normal state and shows a sharp rise by several order of magnitude as transition temperature is reached. The variation of normalized noise with resistance shows that the normal conductor superconductor percolation network fit well with the theoretical 3-D model for the p-noise. The larger k slope attributed to a 3-D model. Improved deposition condition decreases the noise in c-axis oriented thin films by several orders of magnitude. The c-axis oriented film with high-J_c is suitable for fabrication of superconductor devices.

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