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Noise Properties of $YBa_2Cu_3O_{7-\delta}$ Josephson Devices†

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White noise properties of $YBa_2Cu_3O_{7-\delta}$ (YBCO) grain boundary Josephson devices have been studied. Bias voltage *(V)* dependence of the white voltage noise spectral density (S_v) were measured in detail for YBCO dc-SQUIDs and single Josephson junctions on different kinds of substrates with various misorientation angles. It was found that S_v was in good agreement with the thermal noise theory hypothesizing that the device noise was only due to Johnson noise. This implies that the quantum noise can be achieved with optimized YBCO dc-SQUIDS. We have designed a YBCO dc-SQUID with a cross section of junctions as small as 0.1 μm^2. It was predicted that the minimum intrinsic white energy resolution (E" ') should be about Planck's constant (h) at 4.2 K. The actual minimum ε^{ω}, value of 1.76 x 10^{-33} J/Hz = 2.7 h was obtained. This result demonstrates that E" ' of YBCO dc-SQUIDs can be minimized to the order of h.

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During the past few years: there has been considerable progress in the development of thin film $YBa_2Cu_3O_{7-\delta}$ (YBCO) Josephson devices, such as superconducting quantum interference devices (SQUIDs) [1] and high-frequency devices [2]. Pnderstanding the origin of noise, included low frequency and high frequency noise, *is* a key point for their applications. Low frequency (l/f) noise, which determines the performance of SQUIDs, has been studied intensively [3,4]. It was found that the $1/f$ noise in dc-SQUIDS made by high quality epitaxial YBCO thin films was caused by fluctuations of the junction critical current and could be reduced by modulation techniques [5]. High frequency (white) noise properties are useful for understanding the mechanisms of noise and device designs. Here, the white noise properties of YBCO grain boundary Josephson devices (dc-SQUIDS and single junctions) are reported. Also, designs and measurements for low white noise dc-SQUIDs at 4.2 K have been made.

YBCO grain boundary Josephson devices were fabricated on $SrTiO_3$, MgO, YSZ and Si bicrystal substrates with various misorientation angles (θ). YBCO thin films on $SrTiO_3$ and MgO substrates were deposited epitaxially by a pulsed laser ablation method. Buffer layers of YSZ and Y_2O_3 were deposited on YSZ and Si substrates by an electron beam evaporation method. Then, YBCO films were deposited on buffer layers by *DC* or RF

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magnetron sputtering methods. The devices were patterned by a pulsed laser dry etching method. The width (W) of junctions ranged from 1 to 5 μm for YBCO films of 100 ~ 500 nm thick (t). SQUID loop inductance (L) of less than 50 pH was used to reduce the effect of flux noise on white noise.

The devices were mounted in a holder shielded by double mu-metal cylinders and the holder was kept at different heights in a liquid He Dewar to control the operating temperatures(T) of devices. Four-terminal method was used to measure the current(I)-voltage(V) properties and so on. A lock-in amplifier (EG&G PARC 124A) was used to mea-sure the differential resistance $R_D = dV/dI$, flux(@)-voltage(V) transfer function $dV/d\Phi$ and white noise voltage V_n.

Noise measurements were performed on the devices as a function of V and on the SQUIDs as a function of Φ in the frequency ranged 10 ~ 100 kHz. The device was coupled to a low noise room temperature FET preamplifier (NF: SA-400F3, $V_N = 0.7$ nV/$\sqrt{Hz}$ @10 kHz) by a cooled LC resonant circuit [6]. The voltage gain of the tank circuit was $Q_T = 1/2\pi f_0 R_D C_T$, where resonant frequency (f_0) equals to $1/2\pi\sqrt{L_T C_T}$, C_T and L_T are the tank circuit capacitance and inductance, respectively. Q_T values were designed to about 10 and calibrated by measuring the Johnson noise of metal-film resistors. An ACVM mode and tuned band-pass filter of the lock-in amplifier were used to mea-sure the voltage noise. across the tank circuit in a bandwidth much smaller than that of the tank circuit, f_0/Q_T. After subtraction of the preamplifier voltage noise background, the measured $S_v \equiv V_n^2$ was divided by Q_T^2 to give the intrinsic S_v of the devices.

For SQUIDs. the figure of merit is given by intrinsic white energy resolution $\varepsilon^w = S_\Phi/2L$, where $S_\Phi \equiv \Phi_n^2 = S_v/(dV/d\Phi)^2$ *is the* equivalent white flux noise spectral density. From measured S_v, $dV/d\Phi$ and L, values of ε^w can be calculated.

Typical measured intrinsic $S_v - V$ curve at 30 K for a dc-SQUID on MgO bicrystal substrate ($\theta = 24°$) is shown by empty circles in Fig. 1. The loop size is 10 X 30 μm^2 and t = 200 nm, $W = 5\,\mu$m. The critical current (I_c) of SQUID is 70 μA and normal resistance (R_N) is 2.12 Ω. The modulation parameter $\beta_L = 1$ and $L = 29$ pH were obtained at 30 K.

To understand the mechanisms of the white noise, we compare the measured values with thermal noise theory of resistive shunted Josephson junction (RSJ). Assumed that the noise was only originated by the Johnson noise of the resistances, intrinsic S_v of junction is given by [7]:

$$S_v = 4k_B T R_D^2/R \qquad \text{for } eV \ll 2k_B T, \tag{1}$$

where k_B is Boltzmann's constant, e the charge of an electron. V should be smaller than 10 mV for $T = 30$ K.

The calculated result of Eq. (1) is shown by dashed line in Fig. 1. The measured values agree well with the theoretical curve. It implies that S_v for dc-SQUIDS with small L at low bias voltage (≤ 1 mV), which is operation voltage region of SQUIDs and high-frequency devices, is dominant by the Johnson noise. Also, a peak of S_v nearly 1 mV is due to the Fiske resonance of junction.

To study the influence of S_v from L of SQUIDs, S_v of a single junction, which obtained by etched one of the junctions from above SQUID, was measured at 30 K. The measured

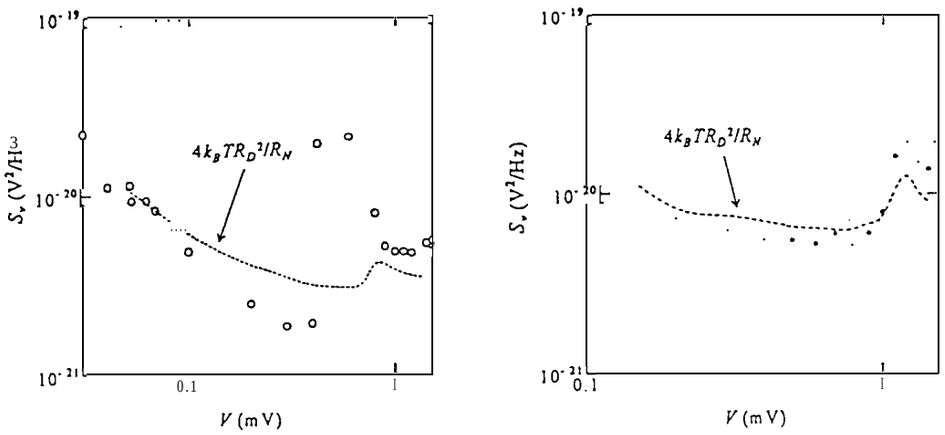

FIG. 1. V dependence of S_v for a dc-SQUID on MgO bicrystal with $\theta = 24°$ at T = 30 K.

FIG. 2. V dependence of S_v at 30 K for a junction obtained by etched one of junctions irom the dc-SQUID as shown in Fig. 1.

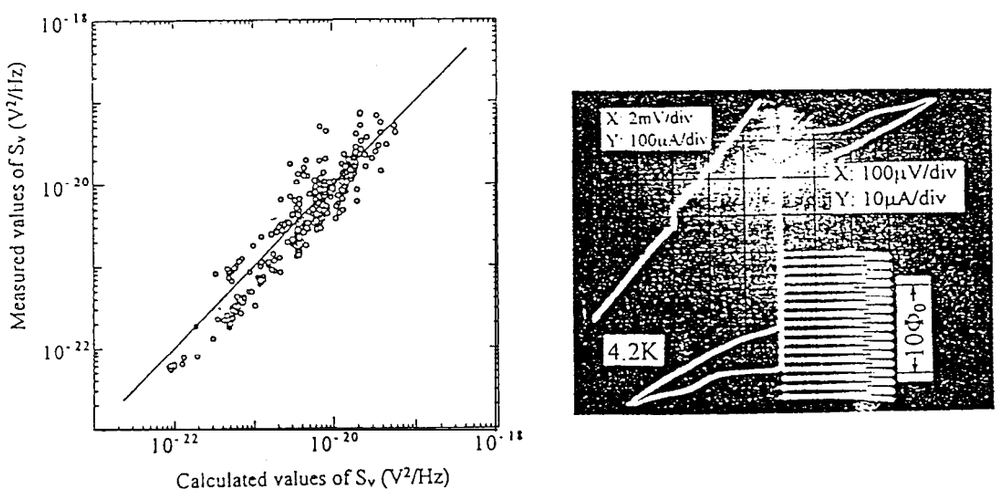

FIG. 3. Measured values and calculated ones of S_v for various devices at different T

FIG. 4. $I-V$ and $V-\Phi$ curves for a SQUID with $W = 1\ \mu m$, $t = 100$ nm and loop size of 9 x 9 μm^2 on YSZ ($\theta = 24°$) at 4.2 K.

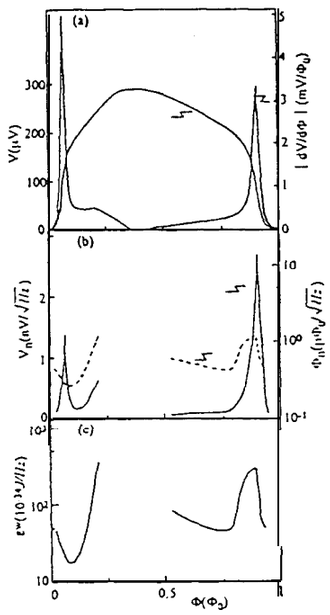

FIG. 5. (a) $V-\Phi$ and $|dV/d\Phi|-\Phi$, (b) $V_n-\Phi$ and $\Phi_n-\Phi$, and (c) $\varepsilon^w-\Phi$ curves for a dc-SQUID as shown in Fig. 4.

and calculated results are shown by solid circles and dashed line, respectively, in Fig. 2. Note that the resistance of the single junction is two times larger than that of the dc-SQUID. Again the good agreement is obtained.

Also, values of measured S_v for several dc-SQUIDs and junctions on various bicrystal substrates are shown in Fig. 3 as a function of the calculated values of Eq. (1). T and V ranged from 4.2 K to 80 K and from 0.01 mV to 1 mV, respectively. The agreement results as shown in Fig. 3 imply that S_v of YBCO devices at Iow bias voltage is also dominant by the Johnson noise of the resistances and the thermal noise theory can be applied to YBCO devices.

A model of the dc-SQUIDS with $\beta_c \equiv 2\pi I_0 R^2 C_J/\Phi_0 \leq 1$, $\beta_L \equiv 2LI_0/\Phi_0 = 1$ and $\Gamma \equiv 2\pi k_B T/\Phi_0 I_0 << 0.05$ predicts that the optimum intrinsic ε^w is given by [8]

$$\varepsilon^w = \gamma h(k_B T/eI_0 R) \tag{2}$$

where I_0, R and C_J are the critical current, normal resistance and capacitance of each junction, $\Phi_0 = h/2e$ is the flux quantum, h the Planck's constant, $7 \sim 1$ for the source of noise is only thermal noise and $\Gamma \ll 0.05$.

ε^w reaches h from Eq. (2) when $I_0 R > 360$ μV at $T = 4.2$ K. $\varepsilon^w = 3.2 \times 10^{-33}$ J/Hz$=5h$ at 4.2 K has been achieved using a SQUID with a cross section area of $10\,\mu m^2$ Pb alloy tunnel junctions for $L = 11$ pH and $I_0 R = 200$ μV[9]. From our measurements, $I_0 R > 500$ μV at 4.2 K for YBCO devices on the bicrystal substrates has been obtained- According to the above results of the white noise, E"' $\sim h$ can be achieved by suitable designs of YBCO dc-SQUIDS.

For $\beta_c \leq 1$ and high I_0R products, C_J or capacitance per unit area (c) should be as small as possible. As c of YBCO junctions on substrates with low dielectric constant (ε_r), such as Si, YSZ and MgO, is about 30 $fF/\mu m^2$ and one order of magnitude smaller than that of junctions on $SrTiO_3$ substrates at 4.2 K, substrates with low ε_r were chosen for designs of low noise dc-SQUIDS. Also, $\beta_c \equiv 2\pi(I_0R)^2c/\Phi_0J_c \leq 1$ means that the critical current density (J_c) must be as large as possible for fixed I_0R and c. However, $\beta_L = 1$ implies that $2J_cAL = \Phi_0$ or $AL = \Phi_0/2J_c$, where $A = W \times t$ is the cross section area of junctions, large J_c thus requires small AL. If the couple to the SQUID is desired for practical applications, then a higher L with very small A is desirable. On the other hand, A must be as large as possible to minimize the effect of kinetic inductance on L and reduce the limit of linewidth for device patterning.

For our YBCO device parameters with $I_0R \simeq 1$ mV, c = 30 $fF/\mu m^2$ and $L = 100$ pH, values of $J_c \geq 10^4$ A/cm^2 and $A \leq 0.1$ μm^2 can be expected to satisfy the conditions for $\varepsilon^w \sim h$. As the minimum linewidth of our etching method is 1 μm, t = 0.1 μm and $J_c = 10^4$ A/cm^2 were chosen for our designed SQUIDs.

The $I-V$ and $V-\Phi$ characteristics at 4.2 K for a dc-SQUID fabricated on a YSZ substrates $(\theta = 24°)$ with $W = 1$ μm, $t = 0.1$ μm and loop size of 9 x 9 μm^2 are shown in Fig. 4. I_c = 32 μA and R_N = 16.7Ω are obtained. L = 91 pH is calculated from modulation depth of I_c and mainly resulted from kinetic inductance as t was less than London penetration depth (λ_L). These values are nearly to designed values. The maximum R_D of about 160Ω, which larger than R_N(16.7Ω), is obtained. Figure 3 shows (a) V and $|dV/d\Phi|$, (b) V_n and Φ_n at $f_0 = 25.4$ kHz, and (c) ε^w as a function of Φ for same SQUID as shown in Fig. 4. The maximum $|dV/d\Phi|$ of 5 mV/Φ_0 is obtained. The minimum ε^w of $2.7h$, corresponds to **1.76** x 10^{-33} J/Hz, compared with the predicted value from Eq. (2).

White noise properties of YBCO Josephson devices have been reported. It was found that S_v in white noise region was in good agreement with the thermal noise theory. This implies that the quantum noise limit can be achieved with YBCO dc-SQUIDS. We have designed and fabricated a YBCO dc-SQUID with $A = 0.1$ μm^2. The obtained minimum ε^w value was about $2.7h$ at 4.2 K. These results are encouraging for YBCO device applications.

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