$1/f$ noise in insulating $YBa_2Cu_3O_{7-\delta}$

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We have studied the $1/f$ noise in underdoped $YBa_2Cu_3O_{7-\delta}$ (YBCO). The YBCO material being studied is the conducting layer in a three-terminal gated device. In sufficiently underdoped devices, the carriers are localized and the main transport mechanism is variable range hopping. In this regime, the normalized power spectrum S_I/I^2 is observed to be linearly proportional to the device resistance R. This scaling is observed as we change R by changing the temperature of the device, the amount of oxygen doping, or the gate voltage. The observed noise is interpreted as being the result of the motion of oxygen atoms in the CuO_x (basal) planes of the YBCO.

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Recently, there has been considerable interest in the normal state properties of underdoped cuprates. In particular, there are several interesting studies reporting the observation of stripe phases in $La_{2-x}Sr_xCuO_4$ and $YBa_2Cu_3O_{7-\delta}$ (YBCO).[1–3] Equally interesting is the observation of a pseudogap in the normal state excitation spectrum of several cuprate superconductors.[4] There are of course other intriguing subjects that need to be more carefully studied in the underdoped regime. For example, the precise temperature dependence of the resistivity in insulating cuprates is often not well characterized. For this reason we recently initiated a series of measurements investigating the temperature dependence of the resistivity of $YBa_2Cu_3O_{7-\delta}$ for $7-\delta<6.4$. We found[5] that in sufficiently underdoped material we clearly observe two-dimensional (2D) Mott variable range hopping (VRH). As we remove even more oxygen, we then observe hopping transport that is dominated by electron-electron interactions.

Another subject that deserves more attention is low frequency resistance fluctuations ($1/f$ noise). Several groups have reported measurements of $1/f$ noise in various cuprate materials.[6–15] Most of these measurements involve studies of optimally doped material,[6,7,9,10] and one of the main issues is the larger than expected noise levels. It is customary to characterize the noise in a material using Hooge's empirical formula[16]

$$S_V/V^2=\alpha/f^\gamma N_c, \tag{1}$$

where S_V is the power spectral density, V is the applied voltage, f is the frequency, γ is a number near or equal to one, N_c is the number of carriers, and the dimensionless parameter α has a value of the order of $10^{-1}-10^{-5}$ in conventional metals. In high-T_c superconductors α is typically found to be $\sim 10^3-10^6$, although an α as low as 10^{-2} has been reported.[14] These very large noise levels are perhaps puzzling and many microscopic models have been reported.[6,7,9,10,12,14,15] These models generally fall into two categories: those describing what is occurring near T_c and those strictly dealing with the normal state well above T_c. In the second category, the noise is often identified as being the result of motion of oxygen atoms in the CuO_x (basal) planes, which contain the Cu-O chains.[12,14]

Despite the recent interest in underdoped cuprates, there are in fact no studies of the $1/f$ noise in the insulating regime $7-\delta<6.4$. This is a regime where the resistivity rises as T decreases, and there is no superconducting transition even at very low T. In this paper we present our measurements of the temperature dependence of the $1/f$ noise in thin films of insulating $YBa_2Cu_3O_{7-\delta}$ having different amounts of oxygen. We find that the normalized current noise S_I/I^2 ($=S_V/V^2$) is linearly proportional to the resistance R of the film. This scaling is observed as we change R by changing the temperature T, by changing the amount of oxygen doping, or by changing the voltage to the gate of our three-terminal devices. Our observations are interpreted as being the result of fluctations in both the number of charge carriers and the mobility of those charge carriers as oxygen atoms move about in the basal planes.

The YBCO material being studied is the conducting channel of a three-terminal device. The substrate is single crystal electrically conducting Nb-doped $SrTiO_3$ (STO) and is the gate G. A 400 nm layer of undoped STO is then deposited on top of G. This is followed by a 50 nm layer of c-axis-oriented YBCO grown epitaxially on top of the STO layer. The device is completed by adding platinum source S and drain D electrodes. Each device has a channel length $1=5\ \mu$m and width $w=90\ \mu$m. Additional fabrication details may be found elsewhere.[5,17,18]

All devices start out with fully oxygenated YBCO. Oxygen is then removed by controlled annealing in Ar at a temperature of 250–350 °C for 1–2 h. The precise amount of oxygen removed δ is not known, but can be estimated from the measured resistivity at room temperature.[19,20] All devices studied for this paper have $7-\delta<6.4$. A list of the final annealing parameters for each device studied is given in column 2 in Table I. In column 1 the label in parenthesis identifies individual devices located on one of several chips that were fabricated. The third column gives the resistiviy ρ of each device at 290 K. The resistivity is calculated from the measured resistance R using the formula $\rho=(dw/1)R$ where $d=50$ nm. Each device has a different starting resistance and a different amount of oxygen. We note that even though devices 1, 3, and 4 have the same final annealing parameters, as indicated in Table I, the annealing history of each device

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TABLE I. Final annealing parameters and starting resistivities at 290 K for four devices.

Device	Final anneal in Ar	ρ(290 K) (Ω cm)
1 (471*m*)	1 h @ 310 °C	16.1
2 (471*r*)	1 h @ 320 °C	6.6×10^5
3 (450*d*)	1 h @ 310 °C	760
4 (450*f*)	same	67

is in fact different and therefore the amount of oxygen and disorder is expected to be different.

The devices are vapor cooled above a bath of liquid helium and the temperature is measured using a Si-diode thermometer. Two-wire dc conductance measurements are made using a battery powered power supply to voltage bias the device and a low noise current preamp to measure the resulting current I. An HP3562A spectrum analyzer is then used to measure the current noise S_I.

Before we discuss the noise properties of the devices listed in Table I we shall first briefly review the temperature dependence of the resistance of these devices. In Fig. 1 we plot the log of R for each device vs $T^{-1/2}$. This is the expected temperature dependence for VRH when *e-e* interactions between the localized carriers are important.[21] In Fig. 1 we see that device 1 obeys the $T^{-1/2}$ dependence very well. Devices 3 and 4 show significant high temperature effects and then begin to follow the expected $T^{-1/2}$ behavior. Device 2 has a very large starting resistance and very quickly reaches the maximum resistance that we can reliably measure. Given the limited range in R, the T dependence of device 2 is not uniquely determined. In a previous publication,[5] we considered other possible temperature dependences for these very resistive devices and we found that the $T^{-1/2}$ dependence was best. Also, even though the temperature dependence of devices 2, 3, and 4 is not as well defined as in device 1, we expect *e-e* interactions to be important in these devices given the convincing evidence that they are important in device 1 and that the starting resistivities of these devices are higher than in device 1. Finally, we note that the data shown in Fig. 1 were taken with the gate voltage $V_g=0$. When we apply a sufficiently negative gate voltage we cleanly observe[5] the $T^{-1/3}$ temperature dependence expected for conventional 2D Mott VRH.[22] In this case, the additional charge added to the conducting channel strongly reduces the effect of *e-e* interations.

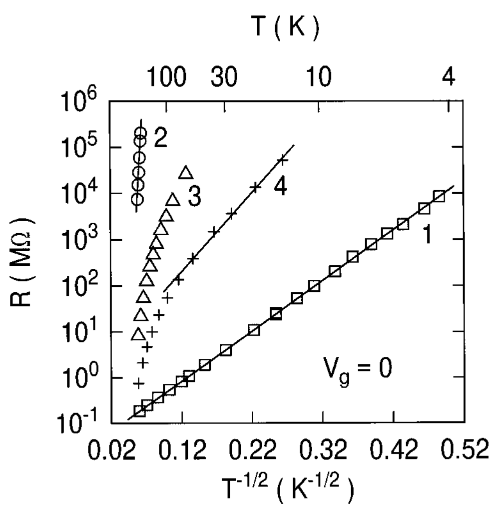

FIG. 1. Resistivity vs $T^{-1/2}$ for four devices. The lines are guides for the eye.

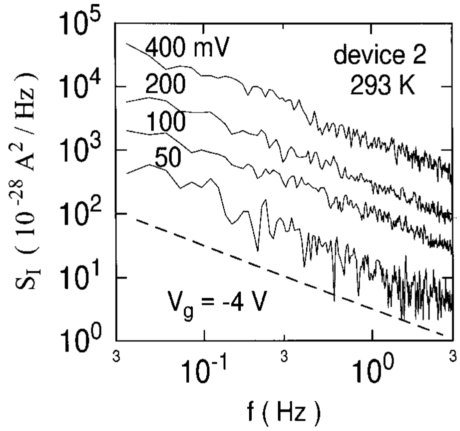

FIG. 2. Noise vs frequency for device 2 measured using four applied voltages. The dashed line shows the expected slope for $1/f$ noise.

Typical noise data are shown in Fig. 2. In this figure, we plot the measured noise of device 2 versus frequency for four different applied voltages. From each noise trace we have subtracted noise data taken with zero applied voltage. This removes both the Johnson noise and any preamp or system noise. The dashed line indicates the expected frequency dependence $S_I\sim 1/f^{\gamma}=1/f$ for $\gamma=1$. The slope γ of the four data traces varies between 1.05 and 1.15 which is typical for our devices. The data also scales with the square of the applied voltage. This is expected if the applied voltage is sufficiently small that we are in the Ohmic regime and if the noise is in fact due to resistance fluctuations. At room temperature, the resistance of device 2 is about 200 MΩ with $V_g=-4$ V and 7 GΩ with $V_g=0$.

In Fig. 3(a) we show the typical effect of changing temperature on the noise characteristics of device 4 with $V_g=-11$ V. These measurements are always taken at low bias to insure Ohmic behavior, and therefore the applied bias V is usually in the range 2–10 mV. We note that $V=4$ mV for the data taken at 7.3, 14.4, and 80.5 K; and $V=10$ mV at 17.6, 170, and 257 K. If we take each noise trace shown in Fig. 3(a) and divide the measured noise by the square of the measured current we obtain the result shown in Fig. 3(b). The ratio S_I/I^2 will be called the ''normalized'' noise. Each trace is now labeled by the sample resistance at which the noise was measured. The lowest trace in Fig. 3(a) measured at 7.3 K now becomes the top trace in Fig. 3(b) with the label 2580 MΩ. The interesting result shown in Fig. 3 is that even though S_I decreases as T decreases, S_I/I^2 increases as T decreases. This occurs because in a hopping system $I=(V/R)\sim\exp[(T/T_0)^{1/n}]$, and therefore S_I/I^2 increases rapidly as we decrease T because I is decreasing exponentially.

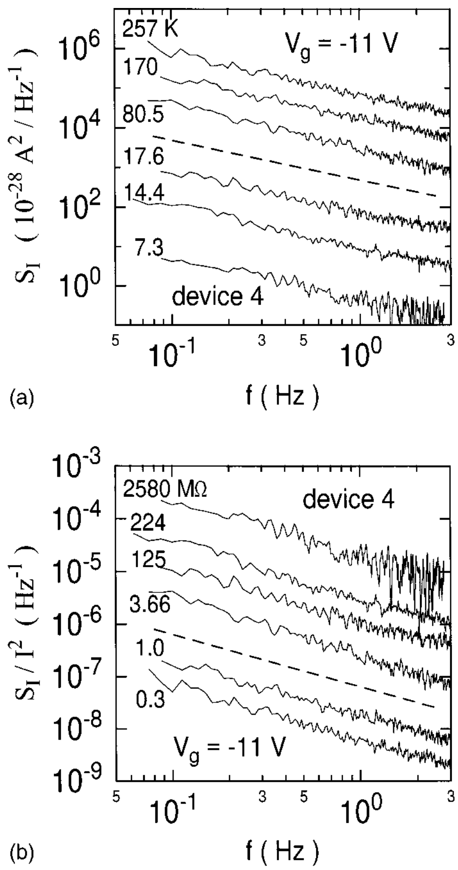

FIG. 3. (a) Noise vs frequency for device 4 at several temperatures. (b) Normalized noise vs frequency at several $R(T)$'s. The noise data S_I are the same as in part (a). The dashed lines show the expected slope for $1/f$ noise.

In the above formula, n depends on the effective dimensionality of the conducting channel and on the strength of the *e-e* interactions.

So far we have changed the noise in our devices by changing T. Another way in which we can change the noise is to change the amount of oxygen in the YBCO layer by annealing in argon. This changes the number of mobile carriers and the amount of disorder. In Fig. 4 we plot measurements of fS_I/I^2 vs R for 3 devices with $V_g=0$. Each device has a different amount of oxygen and a different starting resistivity. For each point, the value of fS_I is obtained from a measurement (trace) of S_I vs f at fixed temperature and is an average of fS_I at 0.1, 0.3, and 1 Hz. For a given device the changes in R are obtained by changing T. (Please note that we shall use the notation fS_I and S_I interchangeably.) The main result shown in Fig. 4 is that S_I/I^2 is linearly proportional to the measured resistance as indicated by the dashed line. This result is observed as we change R either by changing T or by changing the oxygen stoichiometry $7-\delta$. We have considered other possible functional dependences for S_I/I^2, for example, we have tried $\log(S_I/I^2)$ vs $\log T$ (power law in T) and $\log(S_I/I^2)$ vs $1/T$ (activated). However, we then find that the data no longer follow a single universal curve as we change the amount of oxygen.

Before we discuss in detail the observed scaling we shall

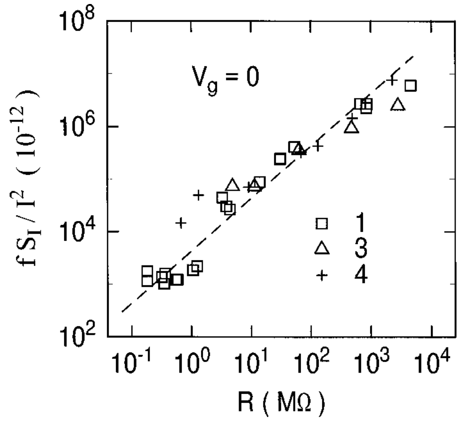

FIG. 4. The average of the normalized noise measured at 0.1, 0.3, and 1 Hz versus the device resistance for three devices with $V_g=0$. The dashed line indicates a linear dependence on R.

first consider one other way in which we can change the noise of our devices—by changing V_g. At fixed T, changing V_g adds charge to the conducting channel near the the YBCO/STO interface and this effects the measured resistance. Figure 5 shows measurements of fS_I/I^2 vs R as we change V_g and then as we change T. At 257 K, the resistance of device 4 decreases from 1.3 MΩ to 136 kΩ as we change V_g from 0 to -18 V. At lower T, the effect is much larger.[5] We note that the +'s in Fig. 5 are the same +'s that appear in Fig. 4 and that most of the dots in Fig. 5 are obtained from the raw data shown in Fig. 3. For completeness, we have indicated the temperatures at which a few of the points were measured. Fig. 5 shows that the data continue to scale reasonably well with R as we change V_g, although there does seem to be a systematic increase in the normalized noise as $|V_g|$ increases. We note that when we change V_g we usually wait several hours before we measure S_I. We do this because there is some initial drift in R at fixed T which lasts about 1/2 hour. The observed systematic increase may therefore be the result of long term drift effects which get worse as we increase $|V_g|$. However, if this were occurring we would expect to see a significant change in the slope of S_I vs f, which is not observed.

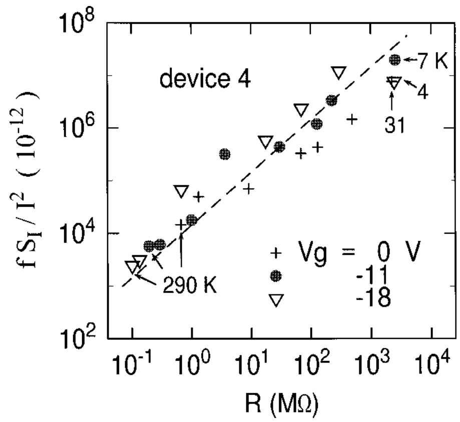

FIG. 5. Normalized noise vs R for device 4 at three applied gate voltages.

We shall now present our interpretation of what is fluctuating; i.e., what is the source of the $1/f$ noise? To do this we shall first briefly consider the standard theoretical framework for $1/f$ noise.[23] An event causing random resistance fluctuations with a characteristic time τ generates a noise spectrum of the form $S\sim\tau/[1+(2\pi f)^2\tau^2]$. If τ is thermally activated, i.e., $\tau(E)=\tau_0\exp(E/k_BT)$, and if there exists a distribution of activation energies $D(E)$ that is roughly constant over a range in energy much larger than k_BT, then

$$S\sim\int\frac{\tau(E)}{1+4\pi^2f^2[\tau(E)]^2}D(E)dE\sim 1/f,$$

where the range of energies over which $D(E)$ is uniform determines the limits of the $1/f$ region. Let us then return to the question: what is fluctuating, or within the context of the above discussion, what is trapping and detrapping? In deoxygenated YBCO we propose that it is the oxygen atoms in the CuO_x planes, which contain the Cu-O chains.[12,14] For $7-\delta<6.4$ there are two main types of fluctuating events:[24,25] (1) free (not aggregated) oxygen atoms that move between unaggregated O(1) sites to O(5) sites and (2) aggregated oxygens that move between O(1) sites within chain fragments and O(5) sites. The first event has a relatively discrete activation energy$=0.1$ eV, and the second has an energy ~ 1 eV. There is a spread in the energies of events of type two because the chain fragments have different lengths. Since the number of unagregated oxygen atoms is small,[24] the second type of event should be the main source of noise. Furthermore, if $E=0.1\,\text{eV}$ and $T=280\,\text{K}$, then $\tau\sim 10^{-11}\,\text{s}$, and therefore events of the first type will not contribute significantly to the observed noise near $f=1$ Hz. The motion of the oxygen atoms changes the coordination number of the Cu atoms in the CuO_x planes which in turn changes the number of (localized) carriers in the conducting CuO_2 planes. However, more importantly, in a hopping system these changes in the number of carriers have a significant effect on the mobility of the carriers. This last point will be made clearer below.

The main result of our paper is the observation: S_I/I^2 scales linearly with R in YBCO material that is sufficiently deoxygenated that VRH is the dominant transport mechanism. This is observed whether we change R by changing T, or by changing the oxygen stoichiometry, or by applying a gate voltage. We can develop some insight regarding this result if we recall the following: $R=\rho(l/wd)=l/(\sigma wd)=l/\{[e\mu(N_c/lwd)]wd\}=l^2/(e\mu N_c)$, and therefore

$$S_I/I^2\sim R\sim 1/N_c\mu, \qquad (2)$$

where μ is the mobility. We can now interpret the observed changes in the normalized noise in terms of changes in N_c and μ. In YBCO, as we change T, the number of carriers changes no faster than a simple power law in T: $N_c\sim T^\kappa$, where $\kappa\leqslant 1$.[20] This is true even if a soft gap develops at E_F.[21] Therefore, in the hopping regime, where $R\sim\exp[(T_0/T)^{1/n}]$, both R and S_I/I^2 increase exponentially as T decreases because μ is decreasing exponentially. We note that in this case the strong T dependence of R and μ is a natural result of VRH transport. However, we would like to emphasize that the observed noise is caused by number fluctuations which in turn cause mobility fluctuations and the overall observed noise is strongly T dependent because μ is.[26] When we change the stoichiometry by removing oxygen the primary increase in noise is the result of N_c decreasing. We also expect the noise to increase because there is now more disorder and therefore μ is smaller. Finally, when we apply a negative gate voltage this adds carriers (holes) to the YBCO and the main effect of doing this is to increase μ, since the additional holes provide additional hopping sites.

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[1] J. M. Tranquada, Physica C **282–287**, 166 (1997), and the references cited therein.
[2] P. Dai, H. A. Mook, and F. Doǧan, Phys. Rev. Lett. **80**, 1738 (1998).
[3] B. Goss Levi, Phys. Today **51** (6), 19 (1998).
[4] T. Timusk and B. Statt, Rep. Prog. Phys. **62**, 61 (1999), and the references cited therein.
[5] F. P. Milliken, T. Doderer, R. H. Koch, and C. C. Tsuei, Phys. Rev. B **62**, 9143 (2000).
[6] J. A. Testa, Y. Song, X. D. Chen, J. Golben, B. R. Patton, and J. R. Gaines, Phys. Rev. B **38**, 2922 (1988).
[7] R. D. Black, L. G. Turner, A. Mogro-Campero, T. C. McGee, and A. L. Robinson, Appl. Phys. Lett. **55**, 2233 (1989).
[8] A. Maeda, Y. Nakayama, S. Takebayashi, and K. Uchinokura, Physica C **160**, 443 (1989).
[9] L. B. Kiss, P. Svedlindh, L. Lundgren, J. Hudner, H. Ohlsén, and L. Stolt, Solid State Commun. **75**, 747 (1990).
[10] Y. Song, A. Misra, P. P. Croker, and J. R. Gaines, Phys. Rev. Lett. **66**, 825 (1991); Phys. Rev. B **45**, 7574 (1992).
[11] C. L. Lin, C. C. Chi, C. C. Chen, and M. K. Wu, Physica C **235–240**, 1789 (1994).
[12] L. Liu, K. Zhang, H. M. Jaeger, D. B. Buchholz, and R. P. H. Chang, Phys. Rev. B **49**, 3679 (1994).
[13] S. Liu, G. Xiong, G. Liu, G. Lian, G. Li, and S. Yan, Solid State Commun. **89**, 507 (1994).
[14] S. Scouten, Y. Xu, B. H. Moeckly, and R. A. Buhrman, Phys. Rev. B **50**, 16 121 (1994).
[15] N. Y. Chen, R. Jonker, V. C. Matijasevic, H. M. Jaeger, and J. E. Mooij, Appl. Phys. Lett. **67**, 133 (1995).
[16] F. N. Hooge, T. G. M. Kleinpenning, and L. K. J. Vandamme, Rep. Prog. Phys. **44**, 31 (1981).
[17] D. M. Newns, J. A. Misewich, C. C. Tsuei, A. Gupta, B. A. Scott, and A. Schrott, Appl. Phys. Lett. **73**, 780 (1998).
[18] T. Doderer, C. C. Tsuei, W. Hwang, and D. M. Newns, Phys. Rev. B **62**, 5984 (2000).
[19] H. Takagi, S. Uchida, H. Iwabuchi, H. Eisaki, K. Kishio, K. Kitazawa, K. Fueki, and S. Tanank, Physica B **143**, 349 (1987).
[20] B. Wuyts, V. V. Moshchalkov, and Y. Bruynseraede, Phys. Rev. B **53**, 9418 (1996).

[21] B. I. Shklovskii and A. L. Efros, *Electronic Properties of Doped Semiconductors* (Springer-Verlag, New York, 1984).
[22] N. F. Mott and E. A. Davis, *Electronic Processes in Non-Crystalline Materials*, 2nd ed. (Oxford University Press, London, 1979).
[23] P. Dutta and P. M. Horn, Rev. Mod. Phys. **53**, 497 (1981).
[24] G. Cannelli, R. Cantelli, F. Cordero, and F. Trequattrini, Supercond. Sci. Technol. **5**, 247 (1992).
[25] B. W. Veal, A. P. Paulikas, H. You, H. Shi, Y. Fang, and J. W. Downey, Phys. Rev. B **42**, 6305 (1990).
[26] We note that since S_I/I^2 does not depend on V_g, it would appear that whether $n=2$ or 3 is unimportant and therefore it is unclear what role e-e interactions play. Ultimately, the key ingredient may be the fact that the electrons are hopping, and the specific type of hopping is irrelevant.