Current-Tuned Superconductor to Insulator Transition in Granular
$Sm_{1.82}Ce_{0.18}CuO_{4-\delta}$ Superconductor

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We have measured transport properties at low temperatures for the granular $Sm_{1.82}Ce_{0.18}CuO_{4-\delta}$ samples belonging to the family of electron-doped superconductors. The effect of applied electrical current on the resistive behavior is investigated. The experimental data are analyzed using a modified form of the theory for a field-tuned superconductor-insulator transition in 2D superconductors. The results suggest a possible electrical-current driven superconductor-insulator transition.

Keywords: Superconductor-insulator transition; Granular superconductors; $Sm_{1.82}Ce_{0.18}CuO_{4-\delta}$

I. INTRODUCTION

The superconductor to insulator transition (SIT) in two-dimensional (2D) superconductors has attracted considerable interest in the last years. Such a transition, which can be tuned by the application of external magnetic field, has been object of interest for both theoreticians [1] and experimentalists [2-4]. As far as the theories are concerned an important contribution to the area is particularly related to the occurrence of the SIT in disordered 2D superconducting systems [1]. The theory predicts a finite temperature scaling law by assuming that a disordered 2D superconductor can be defined in analogy with the field-tuned SIT in disordered 2D superconducting systems. These systems are characterized by two superconducting grains [8,9]. With decreasing temperature, a second transition is observed at $T_{ci}$ and is attributed to the development of Josephson coupling between isolated superconducting islands. Such a transition eventually drives the system to the zero resistance state which is related to the long-range phase ordering of the order parameter through Josephson coupling [8,9].

In these superconducting granular systems the coupling between grains due to the Josephson effect is pronounced and very sensitive to both applied magnetic fields and excitation currents [8,9]. Usually, application of low magnetic fields and electrical currents essentially unafected $T_{ci}$ but results in appreciable changes in the macroscopic properties of the system particularly below $T_{ci}$. Such an effect is usually related to the suppression of the long range order in the phase coherence of the order parameter, where the so called global superconductivity is therefore suppressed [8,9].

Previously, we have reported results suggesting the possibility of a current-induced superconductor-insulator transition in granular high $T_{c}$ superconductors [10,11]. The experimental data were analyzed according to a modified form of the scaling law predicted in Ref. 1, in analogy with the field-tuned SIT transition. The results presented in Refs. 10 and 11 were concerned to granular samples belonging to the hole-doped SI transition. The results presented in Refs. 10 and 11 were concerned to granular samples belonging to the hole-doped system $Y_{1-x}Pr_xBa_2Cu_3O_{7-\delta}$ ($YPr123$). On the other hand, the comparison of the transport properties for both electron and hole-doped superconductors is a current issue [12,13]. In the present work we focus on the SIT in granular samples of the $Sm_{1.82}Ce_{0.18}CuO_{4-\delta}$ compound. This compound belongs to the family of electron-doped cuprate superconductors $R_{2-x}Ce_xCuO_{4-\delta}$ ($R = Nd, Sm, Pr$). The results are compared to the ones obtained for the granular samples belonging to the hole-doped system $YPr123$ [10,11].

II. EXPERIMENTAL PROCEDURE

Polycrystalline samples of $Sm_{1.82}Ce_{0.18}CuO_{4-\delta}$ were prepared by using the sol-gel route [14]. X-ray powder diffraction analysis revealed single phase materials with the T-structure. Details regarding the sample preparation and the reduction process necessary to induce superconducting properties in this compound are given in Ref. 15. The transport measurements were performed by using the Maglab Exa-Oxford platform, by means of the standard four-probe technique using low-resistance ($<1\Omega$) sputtered Au
contacts. The temperature dependence of the electrical resistance, \( R(T) \), was obtained at zero applied magnetic field and in the temperature range \( 3 < T < 30 \text{K} \). The \( R(T) \) curves were taken by using several values of the excitation current, \( 0.2 \leq I \leq 2 \text{mA} \). The voltage versus excitation current (I-V) curves were carried out at zero magnetic field for several values of temperature between 2.5 and 5 K. The characterization of transport properties was complemented performing the resistance versus magnetic field curve, \( R(H) \), at \( T = 5 \text{ K} \) for applied magnetic field from zero up to 0.1 T.

### III. RESULTS AND DISCUSSION

Let us start the discussion by showing in Fig. 1(a) the temperature dependence of the electrical resistance, \( R(T) \), for the granular \( \text{Sm}_{1.82}\text{Ce}_{0.18}\text{CuO}_{4-\delta} \) superconductor. The occurrence of the double resistive superconducting transition is clearly seen in the \( R(T) \) data. A careful inspection of the curve also indicates that the upper superconducting transition occurs at \( T_c \approx 21 \text{ K} \) and that the lower one at \( T_{cJ} \approx 10 \text{ K} \) [8,15]. An important feature of the \( R(T) \) curve concerns the separation between \( T_{ci} \) and \( T_{cJ} \) in temperature. Such a feature, \( T_{cJ} \) far apart from \( T_{ci} \), corresponds to \( \sim 11 \text{ K} \), is unusual in superconducting cuprates, and provides an opportunity to investigate separately both inter and intragranular components for the transport properties. In fact, measurements in the temperature range below \( T_{cJ} \) are particularly useful for studies involving the behavior of the phase of the superconducting order parameter.

The above statement is supported by the results showed in Fig. 1(b), where a hysteresis loop of the electrical resistance under magnetic field \( R(H) \) is displayed. Such a hysteresis loop was measured at \( T = 5 \text{ K} \) and for excitation current of \( I = 0.2 \text{ mA} \). It is important to notice here that the electrical resistance, corresponding to the increasing branch of \( R(H) \), is larger than that corresponding to the decreasing branch, resulting in a clockwise \( R(H) \) hysteresis loop. According to Ref. 11 such a feature is compelling evidence that, below \( T_{cJ} \), the electrical resistance of the granular \( \text{Sm}_{1.82}\text{Ce}_{0.18}\text{CuO}_{4-\delta} \) superconductor is mainly governed by the motion of Josephson vortices.

A deeper insight onto dissipation mechanisms behind in the investigated compound can be obtained from the data displayed in Fig. 2. This figure shows the temperature dependence of the electrical resistance for the \( \text{Sm}_{1.82}\text{Ce}_{0.18}\text{CuO}_{4-\delta} \) compound for several values of excitation current in the range \( 0.2 \text{ mA} \leq I \leq 2 \text{mA} \). The relevant feature of this figure is a well defined change in behavior of \( dR/dT \) from positive (superconducting state) to negative (insulating state) as \( I \) is evolved. We have also found that such a crossover feature in the behavior of \( dR/dT \) occurs for a crossover current \( I_{cr} \sim 1.5 \text{mA} \).

The change in the \( dR/dT \) behavior is reflected in the current-voltage I-V characteristics for the investigated compound. Typical I-V isotherms, taken at several temperatures between 2.5 and 5 K, are shown in Fig. 3. The results also indicate a crossing of the I-V isotherms close to \( I \sim 1.6 \text{mA} \), a value very close to \( I_{cr} \), determined via temperature dependence of the electrical resistance under different \( I \) (see Fig. 2). The crossover behavior observed in \( R(T) \) curves, displayed in Fig. 2 is similar to the ones predicted in a magnetic field tuned superconductor-insulator transition [1]. Moreover, these results resemble the ones reported for the granular \( YPr_{123} \) superconductor [10,11], which suggested a SIT driven by electric current.

Based on these findings, the occurrence of a similar SIT in the granular \( \text{Sm}_{1.82}\text{Ce}_{0.18}\text{CuO}_{4-\delta} \) compound was further investigated. Thus, the I-V isotherms displayed in Fig. 3 were analyzed according to Eq. (1), where the parameter \( B \) has been replaced by the electric current. By doing this, it is supposed that the role of the excitation current in the dynamics of Josephson vortices in granular superconductors is similar to the one of the magnetic field in the dynamics of Abrikosov vortices in two-dimensional superconductors. Within this context, the electrical resistance in the critical regime of the SIT can be written as:

\[
R = R_{cr} f(|I - I_{cr}| / T^{1/\nu})
\]

where \( R = V/I \). \( R_{cr} \) is the resistance at the transition,
FIG. 2: Temperature dependence of the electrical resistance for the Sm$_{1.82}$Ce$_{0.18}$CuO$_{4-\delta}$ compound for several values of the excitation current in the range $0.2 \text{ mA} \leq I \leq 2 \text{ mA}$.

FIG. 3: Current-voltage characteristics taken at several temperatures in the range $2.5 \leq T \leq 5 \text{ K}$. The crossover point $I = I_{cr}$ in the I-V curves is marked with an arrow.

According to Reference 11 and 16, the Eq. (2) can be re-arranged, yielding

$$ f(|I - I_{cr}| / T^{1/z \nu}) $$

is the scaling function such that $f(I = I_{cr}) = 1$, $I_{cr}$ is the crossover excitation current, $z$ and $\nu$ are critical exponents.

Therefore, according to Eq.(4), the critical exponent $1/z \nu$ can be obtained from the linear behavior of $\ln|\frac{d(V/I)}{dI}|_{I>I_{cr}}$ vs. $\ln T$ plots, similar to the one shown in Fig. 4. From the linear fit, one obtains $z \nu = 0.86$ for the granular superconducting compound Sm$_{1.82}$Ce$_{0.18}$CuO$_{4-\delta}$ at zero applied magnetic field. By using the obtained value of $z \nu$ in Eq. (2), the V/I versus the scaling parameter $|I - I_{cr}| / T^{1/z \nu}$ curves are displayed in Fig. 5. A clear collapse of the electrical resistance values onto two distinct branches, distinguishing the $I < I_{cr}$ from $I > I_{cr}$ data, is observed.

An important issue in the present analysis is concerned to the obtained $z \nu$ value, at light of the Ref. 1. According to this reference, the predicted value for this critical exponent is such that $z \nu \geq 1$. Indeed, the $z \nu$ value obtained for the granular samples of the system YPr123 are in accordance with the predictions of the Ref. 1 [10,11]. As described above, for the granular superconducting compound Sm$_{1.82}$Ce$_{0.18}$CuO$_{4-\delta}$, the obtained value for this critical exponent is 0.86. However, it must be noticed that
the scaling result displayed in Fig. 5 is empiric, as well as the correspondent ones for granular YPr123 superconductors [10,11]. In spite of this, the very good scaling fitting observed in Fig. 5, supported by the results of references 10 and 11, suggests the occurrence of an excitation current induced superconductor-insulator transition in the granular superconducting Sm$_{1.82}$Ce$_{0.18}$CuO$_{4−δ}$ compound.

IV. CONCLUSIONS

Based on the transport properties measurements for the granular Sm$_{1.82}$Ce$_{0.18}$CuO$_{4−δ}$ compound, the following conclusions can be drawn:

a) As I evolves a crossover behavior in the I-V isotherms occurs for a specific current value $I_{cr}$ $\sim$ 1.6 mA. The $dR/dT$ curve also exhibits a crossover behavior at $I \sim I_{cr}$;
b) The electrical resistance data as a function of the scaling variable $(|I − I_{cr}| / T^{1/2ν})$ collapses onto two branches, distinguishing the $I < I_{cr}$ from the $I > I_{cr}$ data. Such a scaling behavior suggests the occurrence of an electrical-current-driven superconductor to insulator transition in granular Sm$_{1.82}$Ce$_{0.18}$CuO$_{4−δ}$ compound. Furthermore, the results further indicate that the current-induced SIT can be considered as the dynamical counterpart of the magnetic-field tuned transition;
c) The results are similar to the ones obtained for the YPr123 system, showing a common feature in the SIT for both hole and electron-doped granular superconductors.

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