Low-field transport relaxation measurements in superconducting $Y_1Ba_2Cu_3O_{7-\delta}$

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This paper demonstrates the details of the vortex dynamics correlated to the penetrated state by means of the evolution of time dependence of voltage V for both at low and moderate dissipation levels. The transport relaxation measurements (V-t) have been carried out in a bulk superconducting $Y_1Ba_2Cu_2O_{7-\delta}$ sample as a function of the current (I), temperature (T), and external field (H). It has been observed that the evolution of the V-t data strongly depends on I, T, and H in the investigated regions, and exhibit several interesting features revealing the details of the penetrated state correlated to the motion of flux lines. The unusual data observed in V-t curves have been explained in terms of the plastic flow of the vortices by considering the disorder in the coupling strength between the superconducting grains. In addition, the time evolution of the V-t curves have been discussed in terms of the current and field induced organization of the vortices and it has been shown that the driving current works as an effective temperature by annealing dynamically the corresponding metastable states.

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INTRODUCTION

The magnetic and transport properties of high-T_c superconductors (HTSC's) exhibit many interesting and fascinating behaviors. One of them is the observation of the rapid relaxation of the magnetization. Much effort has been devoted to the study of this phenomenon in order to understand irreversible properties of HTSC's together with the pinning of vortices, vortex dynamics, and structure of the critical state.[1–26] It is well known that high operating temperatures and low pinning energy lead to easy flux creep or flow. Those result in a high rate of magnetization decay, and cause a negative influence on the practical applications of HTSC's.[27–32] It is also well known that the flux dynamics and magnetic relaxation of HTSC's are different than those of low-temperature superconductors (LTSC's). For instance, the time decay of magnetization $M(t)$ is approximately logarithmic for LTSC's which is consistent with the classical Anderson-Kim flux creep model[33] while, for HTSC's, in addition to the logarithmic behavior, a nonlinear logarithmic time decay of magnetization has been reported.[32,34] Therefore, some original models such as vortex glass,[2] vortex lattice melting,[3] and the collective-creep model[5,6] have been proposed to explain the unusual high relaxation rates or functional form of $M(t)$ in HTSC's. A general review on the dynamic of the vortices and flux pinning can be found in the review articles of Blatter *et al.*,[35] and also of Brandt.[36] The relaxation effects in transport measurements have not been attracted much attention as much as the magnetization measurements. However, several studies have been performed on the transport relaxation measurements by many authors.[21–23,25,37,38] In those studies, superconducting glass model,[37] modified flux flow and resistive-weak link models,[38] two kind of flux creep model,[21,22] have been proposed in order to explain the unusual time effects in transport measurements. Furthermore, the recent studies have established the presence of several interesting phenomena associated with the vortex dynamics such as history-dependent time effects,[39] memory effects associated with the amplitude and frequency of the applied current, different response against to alternating or dc currents,[40,41] low frequency noise, etc.[42–44] We note that those observations are not compatible with the physical explanations based on the usual vortex dynamics. Nevertheless, a generic model which accounts for these observations has been proposed by Paltiel *et al.* by considering the experimental studies on a single crystalline sample of $2H$-$NbSe_2$.[45] In this model, it is shown that a competition between the injection of a disordered vortex phase at the sample edges and the dynamic annealing of the metastable state of the disorder by the transport current plays a key role. In addition, this remarkable model explains directly the influence of the dc and alternating current on the vortex dynamics, and can also be applied for HTSC's in investigating the vortex dynamics.

The effect of the current sweep rate and the flux creep on the transport properties have been recently investigated by Zhang *et al.* by solving numerically the nonlinear diffusion equation in one dimension.[25,28] The numerical results obtained by them and their experimental observations, and also that of Kiliç *et al.*[46,47] support that there are remarkable time effects in transport measurements. Our previous study[47] has revealed that further detailed experimental studies are needed to investigate such time effects associated with the vortex dynamics in polycrystalline HTSC's samples. The aim of the present study is to investigate the initial stage of the flux motion in superconducting $Y_1Ba_2Cu_2O_{7-\delta}$ (YBCO) material in detail via the transport relaxation measurements as a function of temperature T, current I, and also magnetic field H on both short and moderate time scales. The present study is a detailed extension of our previous paper[47] and concentrates mainly on the vortex dynamics developing in the intergranular region. It also explores which type of vortices contribute to the relaxation process due to the dissipation level. It exhibits the details of the effect of the driving current, field, and temperature on the evolution of V-t curves.

EXPERIMENT

The YBCO sample was prepared from the high purity powder of Y_2O_3, $BaCO_3$, and CuO by using the conven-

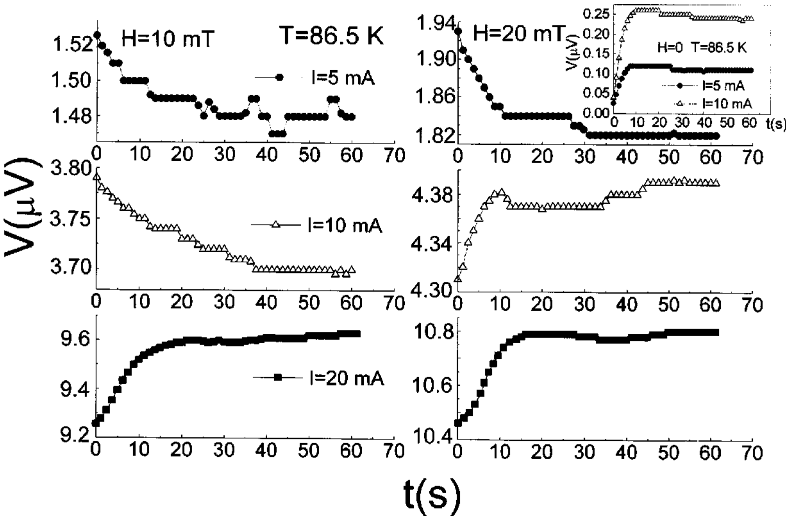

FIG. 1. Evolution of the V-t curves for $H=10$ and 20 mT at 86.5 K for the currents of $I=5$, 10, and 20 mA. Note that the V-t curves which correspond to $I=5$, 10 mA at $H=10$ mT and also the V-t curve taken at $I=5$ mA for $H=20$ mT decrease with time and exhibit several instabilities such as small drops and jumps. The inset shows the V-t curves for $I=5$, 10 mA at 86.5 K for $H=0$. The lines in the figures are guides for eye.

tional solid state reaction. dc electrical measurements were carried out using standard four point method, and performed in a closed cycle refrigerator [Oxford Instruments (OI) CCC1104]. The temperature stability better than 10 mK was maintained during the measurements (OI, ITC-503 temperature controller). In the experiments, Keithley-182 with a resolution 1 nV and Keithley-220 (programable current source) were used in measuring the sample voltage and the applying of the current, respectively. The measurements carried out under the magnetic field were performed by using an electromagnet (OI, N100 electromagnet), and, in all measurements, the field was oriented perpendicular to the transport current I. The details concerning the sample preparation and the experimental setup can be found in the Refs. 46 and 47.

RESULTS

Figure 1 shows the V-t curves measured as a function of the transport currents of $I=5$, 10, and 20 mA for different fields of $H=10$ and 20 mT in a time interval of 0–60 s at $T=86.5$ K. At this temperature range, at low currents, such as $I=5$ and 10 mA, it is observed that the V-t curves taken at $H=10$ mT decrease with time and represent some small jumps, drops together with the several plateaus. Note that the decrease in V-t curves becomes more smooth for $I=10$ mA. At this field and temperature range, we also note that the behavior of the V-t curve for $H=10$ mT changes its form with increasing current, i.e., at $I=20$ mA, and exhibits an inverse effect as compared to that of observed for low currents of $I=5$ and 10 mA. In order to examine further the effect of the external field on the evolution of the V-t curves, the field was increased from 10 to 20 mT. The V-t measurements have been performed at $T=86.5$ K for the same current values (i.e., $I=5$, 10, and 20 mA), which is illustrated on the right side of Fig. 1. It is seen that the voltage for $I=5$ mA decreases again with time, and the V-t curve shows some small instabilities with several plateaus. On the other hand, note that, at this current value, the variation of voltage is fairly smooth up to ~10 s. For $I=10$ and 20 mA, however, it is observed that the shape of V-t curve changes dramatically with an inverse effect as compared to that observed for $I=5$ mA (a similar case is observed for the V-t curve for $I=20$ mA at $H=10$ mT): The voltage increases with time from the start of the measurement up to ~10 s. Hereafter, the voltage shows a tendency to increase with time with several plateaus, in particular, for $I=10$ mA. The tendency of increasing in voltage with time implies that the system still continues relatively to enter into the dissipative state. A similar behavior is also observed more smoothly in the V-t curve for $I=20$ mA at $H=20$ mT. It can be suggested that the instabilities, such as jumps or drops observed in V-t curves, may arise from the measurement system and can be an artifact. In order to test this possibility, the measurements were repeated in the absence of the field ($H=0$) for the currents of $I=5$ and 10 mA. The data associated with this are presented in Fig. 1 as an inset which shows the gradual evolution of the penetrated states as a function of time.

As is seen from the zero field V-t data given in the inset, there is not any significant instability as compared to that of observed in the presence of the field for $I=5$ and 10 mA, despite the fact that there is at least one order difference in magnitude of the voltage between them. Within this picture, such instabilities can be correlated to the increase or decrease in the number of the mobile flux lines, respectively, or attributed to the change in the average effective velocity of the flux lines. At the plateau regions of V-t curves, it can be suggested that the vortex motion becomes relatively more stable. In other words, the moving state locks to a metastable state for a while, during the redistribution process. The term metastable state is used here to describe the motion of the flux lines entering into a state whose properties are determined by the driving current, field, and temperature. On the other hand, at first sight, the most interesting feature seen from the direct comparison between the V-t curve measured at $H=10$ mT and the one at $H=0$ (see the inset in Fig. 1) for the same current values is that there is a remarkable difference in the shape of the V-t curves. As is seen from the inset, at zero field, the voltage increases with time, which implies that the moving state dissipates energy, and reaches a metastable state. However, at $H=10$ mT, the V-t curves mea-

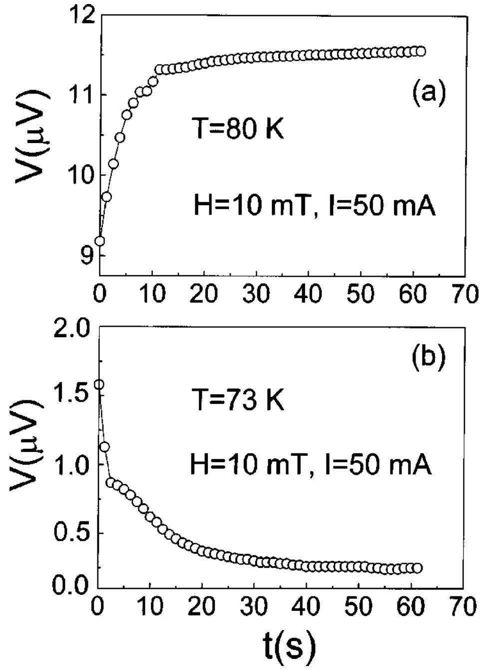

FIG. 2. Influence of temperature on the evolution of the V-t curves at $I=50$ mA and $H=10$ mT (a) for $T=80$ K, (b) for $T=73$ K. Note the change in the shape of the V-t curve with reducing the temperature.

sured for the same current values exhibit an inverse effect, which will be discussed later.

Figures 2(a) and 2(b) shows the influence of the temperature on evolution of the V-t curves under the constant field of 10 mT and the constant current of 50 mA. A dissipative state is seen for the V-t curve at $T=80$ K [Fig. 2(a)] while, at $T=73$ K [Fig. 2(b)], the shape of V-t curve changes dramatically with an inverse effect, as is seen in the V-t curves depicted in Fig. 1 depending on the field and current. Here, the inversion phenomena associated with the change in the shape of V-t curve towards the less dissipative state appears with reducing temperature. In this V-t curve, the decrease in voltage over time also shows that the pinning mostly dominates the relaxation process.

Figure 3 represents the long time evolution (0–300 s) of the voltage for different currents (i.e., $I=50$, 60, and 65 mA) at 80 K for $H=0$. A smooth decrease is observed in voltage as a function of time for all current values, and the system goes into a less dissipative state. Note that, $t \geqslant 50$ s, the voltage becomes approximately independent of time for $I=65$ mA; while, for the other current values, a slight departure is seen. Furthermore, for this temperature range, the relaxation process is relatively slower in the V-t curve for 65 mA as compared to that of observed for other currents. It can be suggested that, in one hand, the self-magnetic flux lines induced by the current are forced to move resulting in the flux motion and, on the other hand, the flux lines are pinned. Whereas, for the current values of $I=50$ and 60 mA, due to the lower magnitude of driving force, the competition between pinning and depinning of the self-magnetic flux lines results mostly in favor of their pinning, and, thus, different relaxation rates and behaviors for the V-t curves are observed.

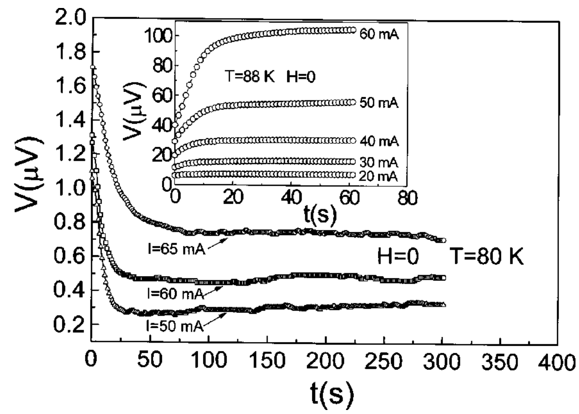

FIG. 3. Long time evolution of V-t curves measured for $I=50$, 60, and 65 mA at 80 K for $H=0$. The inset shows the time evolution of the voltage (V-t) at different constant currents, i.e., $I=20$, 30, 40, 50, and 60 mA, at 88 K for zero field ($H=0$).

As is shown in our previous study,[47] the behavior of the V-t curves at high temperature nearly close to the critical temperature are quite different. A typical example is given in Fig. 3 as an inset. The inset shows a set of V-t curves in a time interval of 0–60 s for different constant currents (i.e., $I=20$, 30, 40, 50, and 60 mA) at 88 K and at zero field ($H=0$). As is seen, first, the voltage increases nonlinearly with time and, then, becomes approximately stable for all current values, although a slight increase in voltage is observed for the high current values of 50 and 60 mA in this region. A comparison between data given in Fig. 3 at 80 K and the data given in inset at 88 K (for instance, for the currents of 50 and 60 mA at $H=0$) reveal the influence of the temperature on the evolution of the V-t curves, as observed in the V-t curves depicted in Fig. 2 under the external field.

Figure 4 shows the V-t curves measured systematically for higher current values of $I=73$, 74, 75, and 78 mA at 80 K for $H=0$. Here again, several current induced metastable states are observed. More interestingly, we see from this figure how the V-t curves evolve with increasing of the current. For instance, the V-t curve corresponding to 73 mA first decreases with time and, then, at around 15 s (marked by an

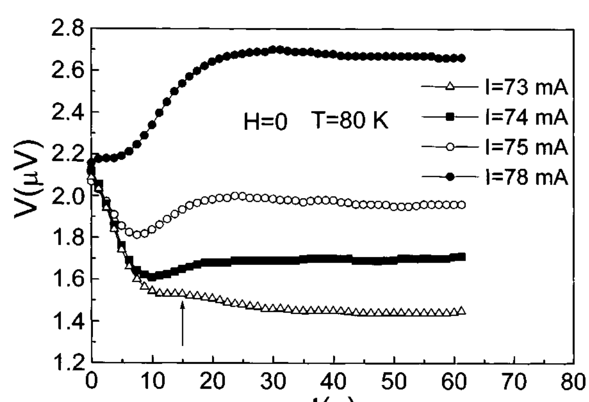

FIG. 4. Influence of the transport current on the evolution of V-t curves for $I=73$, 74, 75, and 78 mA, at 80 K for $H=0$. The lines in the figure are guides for the eye.

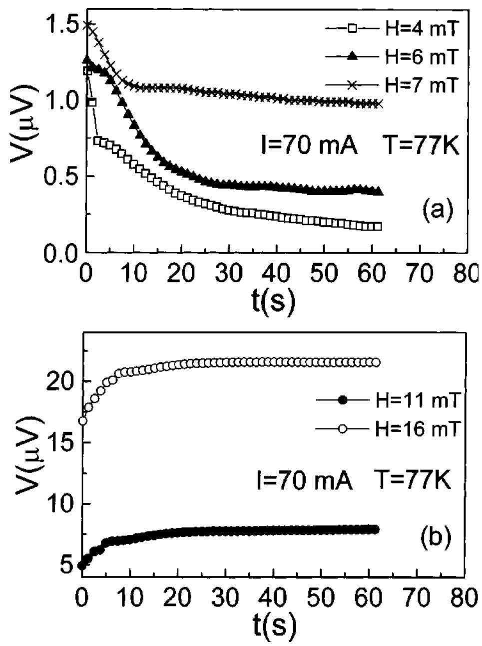

FIG. 5. Influence of the external field on *V-t* curves under the constant current of 70 mA at 77 K (a) for $H=4$, 6, and 7 mT, (b) for $H=11$ and 16 mT. Note the gradual change in the shape of the *V-t* curve with field. The lines in the figure are guides for the eye.

arrow) in the figure, it tends to turn up by giving a trace of that the shape of *V-t* curve will change, and, finally, becomes approximately constant. The *V-t* curve for $I=74$ mA decreases with time and passes through a minimum at around ~10 s. Then, it tends to increase with time by entering from a less dissipative state to more dissipative one, and, finally, it reaches almost a stable state. For $I=78$ mA, the *V-t* behavior becomes totally different as compared to that of observed for $I=73$ mA. It can be suggested that the system enters a more dissipative state as in some *V-t* curves given in Fig. 1, and the *V-t* curves given in Fig. 2(a) and in the inset of Fig. 3. When the *V-t* curves in Figs. 3 and 4 observed at the same temperature region in the absence of the field are evaluated together, we clearly see the influence of the transport current on the evolution of the form of the *V-t* curves, which is another important observation in this study.

Finally, the influence of the external field on *V-t* curves at constant current of $I=70$ mA at $T=77$ K is shown in Fig. 5 for different fields of $H=4$, 6, 7, 11, and 16 mT. This time, we see a gradual evolution of *V-t* curves as a function of external field. At lower fields ($H=4$, 6, and 7 mT), the sample voltage generally decreases with time for a constant field value [Fig. 5(a)]. At the beginning of the relaxation, an abrupt voltage drop is observed especially for the field value of $H=4$ mT. More interestingly, *V-t* curves at low fields show a quasipeak behavior in a relatively narrow time interval, and, then, the voltage decays with time. We suggest that the quasipeak effect can be explained in terms of the transient redistribution effect in the flux configuration.[14] On one hand, for a very short while, the flux lines will easily depin along the weakly pinning centers which allow the formation of the easy motion channels and, on the other hand, the pinning centers and also the pinned flux lines will cause the vortices to slow down and further prevent their motion. At the onset of the relaxation process, such a competition results in a transient effect in flux configuration so that the pinning and depinning processes do not dominate each other. However, as is seen in Fig. 5(b), this behavior totally disappears at high field values together with the change of the shape of the curves and, here, we again see *V-t* curves with two stages. This time, under the constant current and temperature, the external field causes an effect on the evolution of the *V-t* curves, which is similar to that of the current and temperature as is seen in other figures given above.

DISCUSSION

Let us first return to the behavior of the *V-t* curves for $I=5$ and 10 mA at $H=10$ mT and for $I=5$ mA at $H=20$ mT in Fig. 1, which are different than those of the other current values. This difference may be explained within the granular picture as follows.

It is commonly accepted that a weak link can be considered as a type-II superconductor with its own Josephson penetration depth λ_j, its own first critical field H_j ($H_j \sim H_{c1}^W$, the first critical field of the weak link) having the same meaning as the critical field H_{c1}, a decoupling field H_{c2}^W with the same meaning as the critical field H_{c2}, and finally its own edge and surface currents (equivalent to the London current) given by Ambegaokar-Baratoff equation, provided that the length of the junction is sufficiently greater than λ_j.[48–54] When the Josephson barriers are very large and inhomogeneous with vortex trapping regions, so that this kind of junction is closer to the real situation, it will be possible to identify temperature-dependent junction parameters such as H_{c1}^W, H_{c2}^W, etc.[48,53–55] It is well known that the field penetration is extremely complicated in polycrystalline samples, since fields with a strength of less than H_{c1} can penetrate the sample in the intergranular region along the grain boundaries and the places where the superconducting state is weak. However, when the field strength in the grain boundaries exceeds H_{c1}, this causes a partial penetration into the intragranular regions, and the number of vortices in the intergranular region begins to decrease. Under constant current and magnetic field, this process can result in a decrease in sample voltage, because the vortices in the grains are less dissipative with respect to the ones in the intergranular region. The experimental results for $I=5$ and 10 mA at $H=10$ mT and also for $I=5$ mA at 20 mT in Fig. 1 seem to suggest that this kind of physical case is dominant. In this process, note that such a behavior is also current dependent (in addition to the temperature and field strength) since the shape of the *V-t* curves changes dramatically with increasing of the current. A similar case associated with the change in the shape of the *V-t* curve given in Fig. 2(b) appears as an influence of the temperature. On the other hand, the dissipative state observed in the *V-t* curves presented in Figs. 1 and Fig. 2(a) suggests that the transport current exceeds the critical Josephson current J_s. We note that J_s depends strongly on the features of the random weak link network and it decreases with increasing the temperature and, furthermore, it is strongly suppressed by the external field. From this point of view, in Fig. 2, reducing of the temperature from 80 to 73 K would improve the features of the multiply connected network of weak links and would increase its current carrying capability. This case can be evaluated as a suppression of the flux motion and, thus, as an enhancement in magnitude of J_s. In addition, note that some of the V-t curves under the magnetic field given in Fig. 1 clearly reveal the same effect due the increase in the magnitude of the transport current or in the magnitude of the external field. On the other hand, at zero applied field (see inset in Fig. 1), it is seen that the current or associated vortices try to penetrate into the intergranular region for this temperature range, and dissipate energy. Thus, a dissipative state is established in this process. That is, an increase in the sample voltage develops at early times within this picture, and, later, a metastable state is seen for long time values as mentioned previously.

We now focus on the voltage jumps, drops, and plateaus appearing in V-t curves given in Fig. 1. In order to understand the vortex dynamics in an inhomogeneous environment, many extensive numerical studies concerning the current driven molecular dynamics simulations for different pinning regimes have been performed by solving numerically the overdamped equation of motion in 2D.[56–75] According to these many realistic computer simulations,[56–75] at large currents (or under high driving force), there are no plastic deformations, while, at low currents (or under low driving force), vortex configuration becomes highly defective, and it has been shown that the vortex motion follows a channel-like pattern by exhibiting several different plastic flow phases due to the pinning strength.[66,71,72,75] Using the large-scale molecular dynamic simulations, Olson *et al.*[66] showed that the pinning strength causes a transition from plastic flow to semielastic flow. Their study also gives that voltage noise spectrum which is measurable may change with decreasing or increasing the pinning strength. In another detailed study of Olson *et al.*,[69] it is shown that the large voltage noise is obtained due to the softness of the vortex lattice and the magnitude of the driving force when the vortices are in a plastic flow regime. Therefore, we suggest that the instabilities seen in the V-t curves given in Fig. 1 [see also the V-t curve of $H=4$ mT in Fig. 5(a)] originate from the symptomatic transitions between different metastable states, and are an indication of the different plastic flows. This implies that the moving state is not unique as a result of the plastic flow of the vortices.[39,40,76,77] In addition to these instabilities, several plateau regions appear in V-t curves. The drops and jumps in V-t curves can be correlated to the defective flow of the vortices. In this picture, although the driving force is constant, the jumps can be considered as a sudden depinning of some fraction of the flux lines, while the drops can be evaluated as their pinning. At the plateau regions, it can be suggested that the dynamic process remains stable by locking to a short-lived metastable state and this causes evolving of the plateau regions for a short while. Such a physical case associated with the drops, jumps and plateaus could be observed experimentally in I-V curves carried out for different current sweeping rates (dI/dt).[46,47] A typical example which includes the different dI/dt values of 0.45, 0.18, and 0.09 mA/s is given in Fig. 6 at $T=88$ K and at zero

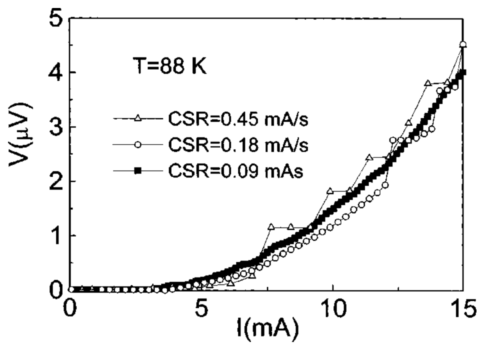

FIG. 6. Evolution of the I-V curves at $T=88$ K as a function of different sweep rates: $dI/dt=0.45$, 0.18, and 0.09 mA/s. Note the disappearance of the voltage jumps and plateaus with decreasing dI/dt.

field. In Fig. 6, several jumps and plateaus which manifest themselves as a discontinuity in I-V curves are seen as a function of dI/dt. Note that the instability of the moving state decreases with decreasing the dI/dt and, finally, disappears for the CSR of 0.09 mA/s. We suggest that there might be a correlation between the physical effects (jumps, drops, and plateaus) appearing in I-V curves measured for different values of dI/dt[46,47] and that of the V-t curves. In fact, fast current ramps used in measuring the I-V curves are crucial for probing the metastable states, and such measurements show directly a snapshot of the instantaneous of the flux line configuration before the system can reorganize itself. On the other hand, at slow ramps, the flux lines find enough time to reorganize themselves since the experiments are carried out on large time scales. In V-t measurements, at constant driving current, the pinning potential seen by the vortices is reduced over time, which leads to gradual depinning of the vortices. Here, it can be suggested that the driving current serves as an effective temperature by annealing dynamically the corresponding metastable state. A similar discussion is given in a recent study in the frame of a generic model by Paltiel *et al.*,[45] and it is shown that the competition between the contamination effect along the grain boundaries and annealing process due to the driving current can also cause such instabilities.

We return to the V-t data given in Fig. 4. In this figure, a remarkable change in the shape of the V-t curves as a function of current can be evaluated as a direct evidence of the dynamic annealing effect of the driving current. Here, the driving current has a deterministic property in the evolution of the V-t curves. We would like to note that a phenomenon associated with the deterministic property of the transport current was reported in a recent study in single crystalline sample of 2H-$NbSe_2$ by Xiao *et al.*[41] In that study (although it considers a different sample and regime), it is shown that the transport current enables the vortices to organize themselves into a new accessible state and has an effective deterministic property in vortex dynamics. Further, the deterministic property of the applied current is argued by Henderson *et al.*[39] and also in detail by Paltiel *et al.*[45] It is shown that the applied current causes two main effects: one is the injection of the disordered vortex phase at the sample edge so called contamination effects (in our case, the sample edge corresponds to the grain boundaries in a polycrystalline sample), and the other is the annealing of the metastable disorder, while the current flows in the bulk, so called as annealing process. In the present study, with increasing the current, the functional form of the V-t curves in Fig. 4 gradually changes, in particular, the one at $I=78$ mA becomes similar to that of the V-t curves measured at $T=88$ K for $H=0$, which are given in the inset of Fig. 1. This proves that the driving current serves as an effective temperature in the usual sense as in the statistical mechanics so that the results are in favor of the recent model proposed by Paltiel *et al.*[45]

Furthermore, similar annealing effects are observed in field dependence of the V-t curves presented in Figs. 5(a) and 5(b). These results can also be interpreted in terms of the field driven organization of the vortices. At constant current, this time, the external field anneals dynamically the corresponding metastable state as in the case of the driving current. In this scenario, at low fields, the pinning of the vortices is still effective and this case manifests itself as a decrease in the effective vortex velocity, while, with increasing the field, the pinning potential is gradually smoothed out, which results in provoking of the depinning of the vortices and, also relatively more ordered vortex motion. Thus, this dynamic process created by the field which serves an effective temperature causes to change in the form of the V-t curve. Note that the form of the V-t curves measured at $H=11$ and 16 mT are similar to that of the V-t curves given in the inset of Fig. 3. On the other hand, we also note that the dynamics of the flux lines through the sample depends on the quality of the sample together with the disorder in the coupling strength between the superconducting grains (i.e., Josephson coupling effects), and also the macroscopic dimensions of the sample to be investigated.[46–48]

It is reasonable to assume that the time decay of the voltage appearing in V-t curves given in Figs. 1, 2(b), 3, and 5(a) and also some V-t data of Fig. 4 arises from the flux lines which lose their capability of moving during this process due to the magnitude of the applied current together with the field and temperature range. This is significant, in particular, at early times of the relaxation measurement. In this complicated process, some of the vortices are moving, while some of them remain gradually pinned in time. That is, the pinning and depinning process of the flux lines take place together, but develops in favor of the pinning process at early times of the relaxation. Thus, the number of the mobile flux lines drops significantly. After reaching a metastable state, the ratio of the number of the flux lines pinned to the number of the ones depinned (mobile flux lines) becomes almost constant. In the temperature and field region to be investigated, this naturally leads to the suggestion of the presence of the several dynamical phases of the vortices, which are related to the plastic flow, immobile, or pinned flux configuration so that those will have dramatic effects on transport measurements such as I-V curves, magnetoresistance, etc.[23,25,28,46,47]

We now discuss the type of the vortices which contribute to the transport relaxation process. As is well known, the intergranular currents can be determined by means of the transport measurements (resistivity technique) since the intergranular current densities are rather low and, therefore, easy to measure directly without excessive Joule heating. The intergranular currents can also be measured by the low field magnetization measurements. For HTSC's, it is commonly accepted that the Josephson vortices can be naturally generated in the weak link structure of the granular materials, and, even in single crystals, the vortices lying between Cu-O layers are in Josephson character.[35,36,46–48,54] The most characteristic feature of Josephson vortices is that they have no normal core, whereas, inside the grains, the vortices evolve in the form of Abrikosov.[35,36,46–48,54] Experimentally, in granular samples, the relaxation of Josephson vortices as investigated by the low-field hysteresis cycle is extremely weak, and difficult to measure.[48,54] The reason can be explained as follows. In the usual flux creep model (applied mostly for the Abrikosov vortices) the jump distance (or the hopping distance) of the vortex is very short so that it is about the order parameter. For Josephson vortices, it must be of the order of the Josephson length, hence much larger than for the usual case. Therefore, we suggest that the time effects observed in V-t curves given in this paper originate effectively from the intergranular region and should reflect naturally the relaxation of the Josephson vortices.

We note that such flux dynamics described above can be confirmed by the direct imaging methods. One of them is the magneto-optical measurements.[78–81] As is well known, the local behavior of the magnetic flux and the flux patterns are determined directly from the magneto-optical imaging measurements with a high spatial resolution. In a recent study, Bobyl *et al.* have investigated the flux and current density profiles in YBCO thin film grown on $LaAlO_3$ substrate by using the magneto-optical imaging method and analyzed their data within the critical state model.[81] In their experiments, the pulse current with different duration times have been used. Their experimental observations concerning the flux profiles support that there is nonstationary flux distribution inside the sample and also significant time effects related to the relaxation phenomenon as a function of both amplitude of current and duration time.

Finally, in addition to the usual transport measurements such as temperature dependence of resistance, I-V characteristics, magnetoresistivity, etc., we would like to express that the V-t characteristic is a candidate to be another powerful measurement method in characterizing the superconducting samples. Thus, in addition to the M_{irr}-t measurements, the transport relaxation measurements concerning V-t curves will help us to understand the irreversible properties of superconductors and the details of vortex dynamics.

CONCLUSION

In this paper, we have measured the transport relaxation (V-t) of a bulk superconducting YBCO sample as a function of transport current, temperature, and the external field. Depending on these parameters, it is observed that, in some cases, the developing voltage increases nonlinearly with time which is an indication of the pinning and depinning of the flux lines and then becomes nearly stable which is called metastable state, while, in some cases, the voltage decreases as the time progresses. The unusual data observed in V-t curves have been explained in terms of the plastic flow of the flux lines by considering the disorder in the coupling strength between the superconducting grains. In addition, the time evolution of the V-t curves has been discussed in terms of the contamination and annealing effects induced by the current and field associated with a recent model proposed by Paltiel *et al.*[45]

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