Photoresponse of $YBa_2Cu_3O_{7-\delta}$ films in the flux-creep regime

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We have studied the effect of continuous illumination with visible light on the flux motion in an epitaxial $YBa_2Cu_3O_{7-x}$ film over a wide range of temperatures. A ring-shaped sample was used to obtain voltage-current (V-I) characteristics without applying electrical contacts. It is shown that the illumination is substantially altering $d \ln V/dI$ at low temperatures and low currents. This effect is practically independent of the light intensity between 5 and 100 klux and it remains appreciable even for illuminations as weak as 30 lux. The effect weakens with increasing temperature and vanishes at approximately 35 K.

I. INTRODUCTION

The response of high-temperature superconductors (HTSC's) to illumination has attracted considerable attention and first publications on this subject appeared soon after the discovery of HTSC's.[1,2] This interest has partly been stimulated by the possibility of practical applications. At the same time, investigations of these effects provide important information concerning the intrinsic physical properties of HTSC's. When considering mechanisms of the interaction of light with superconductors, one should distinguish between an equilibrium heating of the sample by illumination, i.e., a bolometric effect, and a nonequilibrium, i.e., nonbolometric situation. In this work only the latter type is considered.

Two types of experiments studying photoresponse of HTSC's have been made previously. First, the influence of continuous illumination on resistive transition curves $R(T)$ has been investigated in Refs. 1 and 3–11. These experiments are obviously limited to temperatures near T_c. Second, the method of applying short laser pulses permits to study relaxation phenomena on a very short time scale in a wide range of temperatures.[2,12–24] Much of this work has been reviewed in Refs. 25–28. While the interaction of light with conventional superconductors is well understood (see, e.g., Ref. 29 and references therein), the situation for HTSC's is still far from being clear.

In this paper we present an experimental study of the effect of continuous illumination on the flux creep in HTSC's at low temperatures. This effect was discovered by Yurgens and Zavaritskii on $Bi_2Sr_2CaCu_2O_8$(BiSCCO) single crystals[30] and later it was also observed on $YBa_2Cu_3O_{7-\delta}$(YBCO) films.[31] The observation of the same effect for both these two rather different copper-oxide materials suggests that the high sensitivity of the flux creep to illumination is a fundamental property of HTSC's. Some of the features of the illumination effect are rather puzzling. The observation of the effect in BiSCCO single crystals with a thickness of about 30 μm, more than two orders of magnitude thicker than the penetration depth of visible light,[30] is surprising because one would rather expect that the effect of illumination is negligible in samples with this thickness. However, this is clearly not the case and the illumination effect is of similar strength in the BiSCCO single crystals as it is in about two orders of magnitude thinner YBCO films.[31] As will be shown below, the effect decreases rapidly with increasing temperature and it disappears at $T \approx 35$ K, well below the superconducting transition temperature of the YBCO film. The influence of illumination is very efficient since even an illumination of a few μW/cm^2 considerably accelerates the flux-creep rate. While the reports in Refs. 30 and 31 may be regarded as demonstrations of the effect, the present work aims at a more thorough and quantitative investigation of its dependence on illumination intensity and temperature.

II. EXPERIMENTAL SETUP

The sample under investigation here is similar to that used in Ref. 31. It is a ring-shaped YBCO film with a thickness of 0.3 μm. The external diameter of the ring is 10 mm and its width is approximately 2 mm. The ring width was not perfectly uniform around its circumference, with maximum variations of about 0.3 mm.

The sample was mounted on a copper sample-holder, which was placed into a brass chamber containing helium exchange gas. This chamber itself was situated inside a vacuum chamber to prevent a direct contact with liquid helium. The whole setup was inserted into a standard glass helium Dewar. A copper wire of 0.5 mm diameter and a few centimeters length provided the heat transfer between the internal brass chamber and the helium bath. A LakeShore diode thermometer, fixed to the sample holder, was used to monitor the sample temperature. A heater in the form of a bifilar coil made of constantan wire was wound onto the internal chamber. A computer based temperature controller was used to maintain constant temperatures. In this way it was possible to keep the sample at chosen temperatures above 4.4 K. Diode thermometers are rather sensitive to magnetic field and to diminish this effect, the thermometer was surrounded by a miniature magnetic field shield. As a result, the effect of an external magnetic field of 0.1 T (see below) on temperature readings was less than 0.1 K at any temperature. The remaining difference was taken into ac-

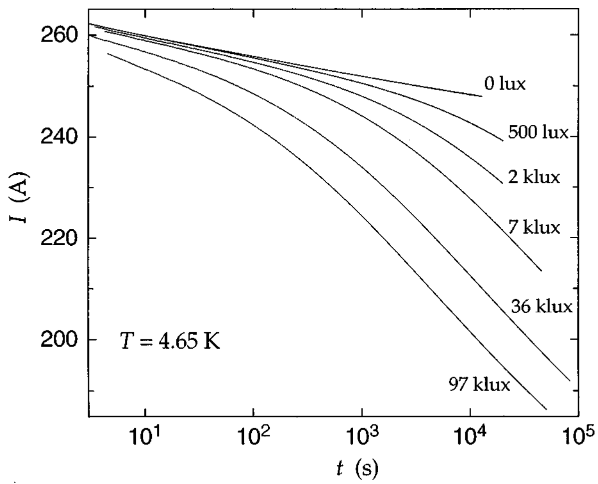

FIG. 1. Time dependence of the current in the sample after switching of an external magnetic field of the order of 0.1 T.

count by the temperature controller.

A halogen-lamp light source, placed outside the cryostat, in combination with a fiberoptic light guide passing through the upper flange of the cryostat, was used to illuminate the sample. To adjust the light intensity, diaphragms were placed into the light path. An additional output in our fiberoptic bundle was used to control the light intensity with a ''Goldilux™'' light meter produced by Oriel corporation. The experiments were made with white visible light (wavelengths between 450 and 700 nm). For the spectral characteristics of our light source, 1 klux is equivalent to approximately 600 μW/cm^2.

An external magnetic field H_0, oriented perpendicularly to the ring plane was used to induce a current I in the ring. At the beginning of an experimental run a magnetic field of 0.1 T was switched on for 10 to 30 sec, with the sample being kept at a constant temperature. This value of the magnetic field was high enough to penetrate the cavity of the ring-shaped sample. Then, the external magnetic field was switched off thus inducing an electrical current in the ring. This current defines the magnetic induction trapped inside the ring cavity, which was monitored as a function of time. We used a LakeShore 450 Gaussmeter with a standard cryogenic Hall probe to measure the magnetic field inside the ring cavity.

III. RESULTS

Because of flux pinning, the superconducting YBCO film remains in the mixed state even after switching-off the external magnetic field. Due to the flux creep invoked by the induced current, magnetic flux escapes from the ring cavity and, consequently, the current slowly decays with time. Examples of current decay curves with and without illumination are shown in Fig. 1.

The advantage of choosing a ring geometry for this type of experiments is clearly the possibility to obtain voltage-current (V-I) characteristics of the sample without applying electrical contacts. Moreover both the analysis and interpretation of the V-I curves are much less dependent on considering different models than the usually measured curves of magnetic relaxation. The total voltage around the ring is defined by the simple formula.

$$V = L\frac{dI}{dt}, \tag{1}$$

where L is the inductance of the sample. For a ring the inductance (in Henry) can be written as

$$L \approx 2\times 10^{-9}\pi D[\ln(\pi D/d)-1], \tag{2}$$

where D is the average ring diameter and d is its width, both in centimeters. For our sample, $L\approx 8$ nH. The experimental $I(t)$ data may straightforwardly be converted into V-I curves, examples of which for two temperatures and a set of different illumination intensities are shown in Fig. 2(a). It should be noted that the resulting V-I characteristics were independent of the time period for which the magnetic field was switched on, if this time was longer than a few seconds. We have also checked that our results did not depend on the absolute value of H_0 in the range $0.09\,\mathrm{T}<H_0<0.11\,\mathrm{T}$.

The range of currents that can be measured in this way is limited by the decay rate of the current. For practical reasons, high voltages, i.e., very high current decay rates are difficult to monitor and, as one can see in Fig. 1, very low voltages are practically excluded because it is not feasible to wait long enough to reach sufficiently low current decay rates. In principle we are mainly interested in the low voltage parts of the V-I characteristics, because the effect of illumination is more obvious in this range. As it is shown in Fig. 3, it turned out to be possible to speed up the decay process by switching to a more intense illumination for some time and then to measure dI/dt for low illuminations. With this procedure the lower limit of measured voltages was about 10^{-14} V. The V-I curves obtained in this way are presented in Fig. 2(b). In this case we have a set of experimental points for each light intensity instead of continuous curves, which makes the measurements less accurate. The solid lines in this figure represent the V-I characteristics recorded without the speed-up procedure. The data presented in Fig. 2(b) show that the effect of illumination on the derivative $d\ln V/dI$ remains almost the same down to light intensities as weak as 30 lux. The V-I curves for higher temperatures shown in Fig. 2(c) demonstrate a rapid decrease of the illumination effect with increasing temperature.

Although the sample was surrounded by ^{4}He gas for heat exchange, we cannot exclude some overheating of the sample by the radiation at higher illumination intensities. This overheating, which is estimated to not exceed 0.5 K under any circumstances, may partly be responsible for a shift of V-I curves to lower currents with increasing illumination [Fig. 2(a)–2(c)]. It is, however, important to note that these postulated temperature enhancements obviously do not change the slope $d\ln V/dI$ [see Fig. 2(a)] and therefore, possible overheating effects are not important in the discussion of the data presented below.

Without illumination, the V-I curves, plotted as $\ln V$ versus I in Figs. 2(a)–2(c), are almost straight lines, in agreement with theoretical predictions for the flux creep regime.[32–36] An increase in temperature leads to an almost parallel shift of the V-I curves to lower currents. Both illumination as well as an increase in temperature enhance the flux creep rate, but in completely different ways. This difference, which can easily be recognized in Fig. 2(a), clearly

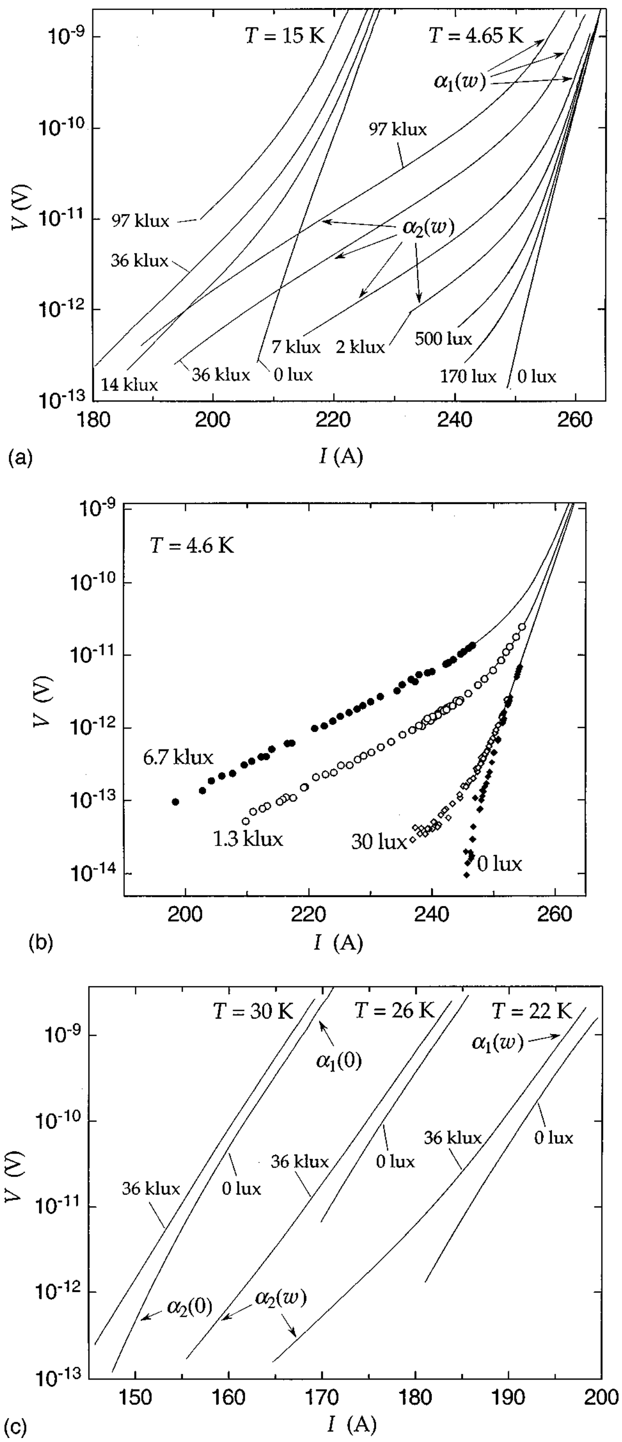

FIG. 2. (a)–(c) Semilogarithmic plot of the voltage versus current for different temperatures and intensities of illumination. Arrows in (a) and (c) show the parts of the curves, for which the parameters α_1 and α_2 were calculated (see text for details).

demonstrates that the effect of illumination is not related to an overheating of the sample by light.

To simplify the notation we shall use $\alpha(w)$ and $\alpha(0)$ for the slopes $d \ln V/dI$ recorded with and without illumination, respectively. The parameter w quantifies the light intensity. The effect of illumination is particularly visible at low temperatures where the V-I characteristics for the illuminated sample exhibit two different asymptotic behaviors for high and low currents. In both limits the curves can be well approximated by an exponential variation, but with very different values of $d \ln V/dI$, as it is clearly seen in Fig. 2(a) and Fig. 2(b). We thus introduce $\alpha_1(w)$ and $\alpha_2(w)$ to denote the values of $\alpha(w)$ at high and low currents, respectively. Both $\alpha_1(w)$ and $\alpha_2(w)$ are different from $\alpha(0)$ and, therefore, the ratio $\alpha(0)/\alpha(w)$ can be used to characterize the magnitude of the illumination effect. We consider the effect of illumination separately at high and low currents. Since the $\ln V$ versus I curves without illumination are not exactly straight lines, it seems more appropriate to calculate the ratios $\alpha(0)/\alpha(w)$ using the slopes of the curves evaluated at the same current. The relevant values of $\alpha(0)$ are denoted as $\alpha_1(0)$ and $\alpha_2(0)$, for high and low currents, respectively. At low temperatures we had to extrapolate the V-I characteristics to lower voltages to evaluate $\alpha_2(0)$. The temperature dependencies of $\alpha_1(0)$ and $\alpha_2(0)$ are shown in Fig. 4.[37]

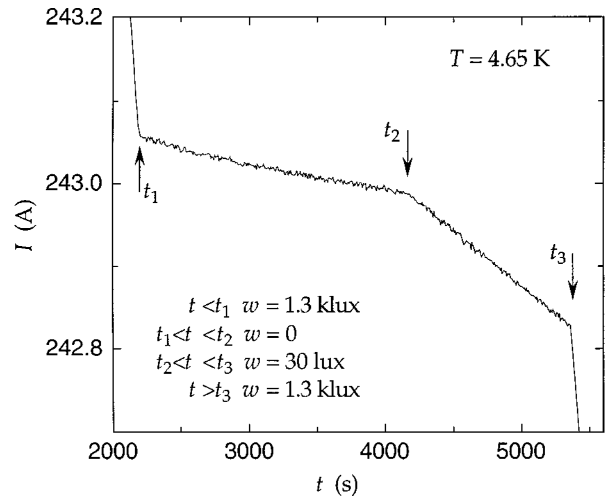

FIG. 3. Time dependence of the current for different levels of illumination. The arrows indicate the change of illumination ($t=0$ is chosen arbitrarily).

The ratios $\alpha_1(0)/\alpha_1(w)$ and $\alpha_2(0)/\alpha_2(w)$ obtained at constant temperature are plotted versus light intensity in Fig. 5(a) and Fig. 5(b), respectively. At high currents the effect of illumination, as expressed by the ratio $\alpha_1(0)/\alpha_1(w)$, is varying considerably with the light intensity and it practically vanishes at $w \approx 100$ lux. The intensity dependence of $\alpha_2(0)/\alpha_2(w)$ is quite different with an almost logarithmic increase of the ratio with increasing intensity of illumination for low w and a saturation for $w \gtrsim 5$ klux. Quite surprisingly the ratio $\alpha_2(0)/\alpha_2(w)$ remains considerably greater than 1 down to the lowest investigated levels of illumination.

While the slopes of the $\ln V$ versus I curves remain almost constant at low currents, the absolute value of the voltage at a given current decreases with decreasing intensity of illumination. Figure 5(c) shows the voltage at $I=230$ A as a function of illumination at $T=4.65$ K on double logarithmic scales. For a wide range of w we note a linear dependence of the voltage on the intensity of illumination. Because the voltage is proportional to the flux creep rate, our observation implies that in this case the flux creep rate induced by illumination is proportional to the light intensity.

Figure 6(a) shows the ratio $\alpha_2(0)/\alpha_2(w)$ for a number of fixed levels of illumination as a function of inverse temperature. Because $\alpha_2(w)$ does not depend on w at illuminations

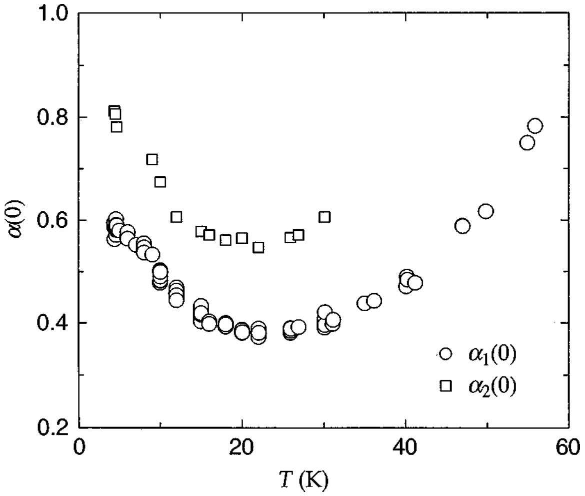

FIG. 4. The variation of $\alpha_1(0)$ and $\alpha_2(0)$ with temperature.

of the chosen intensities, the experimental points for different w merge onto the same curve. For $T \gtrsim 14\,\mathrm{K}$, $\alpha_2(0)/\alpha_2(w)$ depends linearly on $1/T$ and it reaches the value of 1, implying the disappearance of the illumination effect, at a temperature $T \approx 35\,\mathrm{K}$. The diagram in Fig. 6(b), displaying $\alpha_1(0)/\alpha_1(w)$ for $w = 36$ klux, shows that this ratio is a linear function of $1/T$ across the whole investigated temperature range, reaching the value of 1 at approximately the same temperature as does $\alpha_2(0)/\alpha_2(w)$. We thus conclude that the effect of illumination on the flux creep in YBCO films vanishes at a temperature of approximately 35 K, well below $T_c \approx 92\,\mathrm{K}$.

IV. DISCUSSION

The flux-creep situation in the mixed state of a type-II superconductor is met if $I < I_c$, i.e., when the vortices are fixed at pinning centers and the only way for them to move is by hopping over potential barriers. Two different possible one dimensional profiles of potential barriers $u(x)$ are shown schematically in Fig. 7(a) and 7(b), where $u(x)$ denotes the potential energy as a function of the space coordinate x. The hopping may be due to either thermal activation or quantum tunneling. In both cases the probability of hopping depends exponentially on the heights of the potential barriers, which define the activation energy U of the hopping process. For the thermal activation the hopping frequency is

$$\nu = \nu_0 \exp(-U/kT), \tag{3}$$

where ν_0 is the attempt frequency. In the case of quantum creep, U/kT should be replaced by the Euclidian action of the tunneling process.[35] Calculations show that the activation energy for the motion of bundles of vortices is considerably less than that for single vortices.[32–36] That is why the flux creep should usually be regarded as a cooperative hopping of vortex bundles.

Taking into account that the voltage is proportional to the hopping frequency we can rewrite Eq. (3) as

$$\ln \frac{V}{V_0} = -\frac{U}{kT}, \tag{4}$$

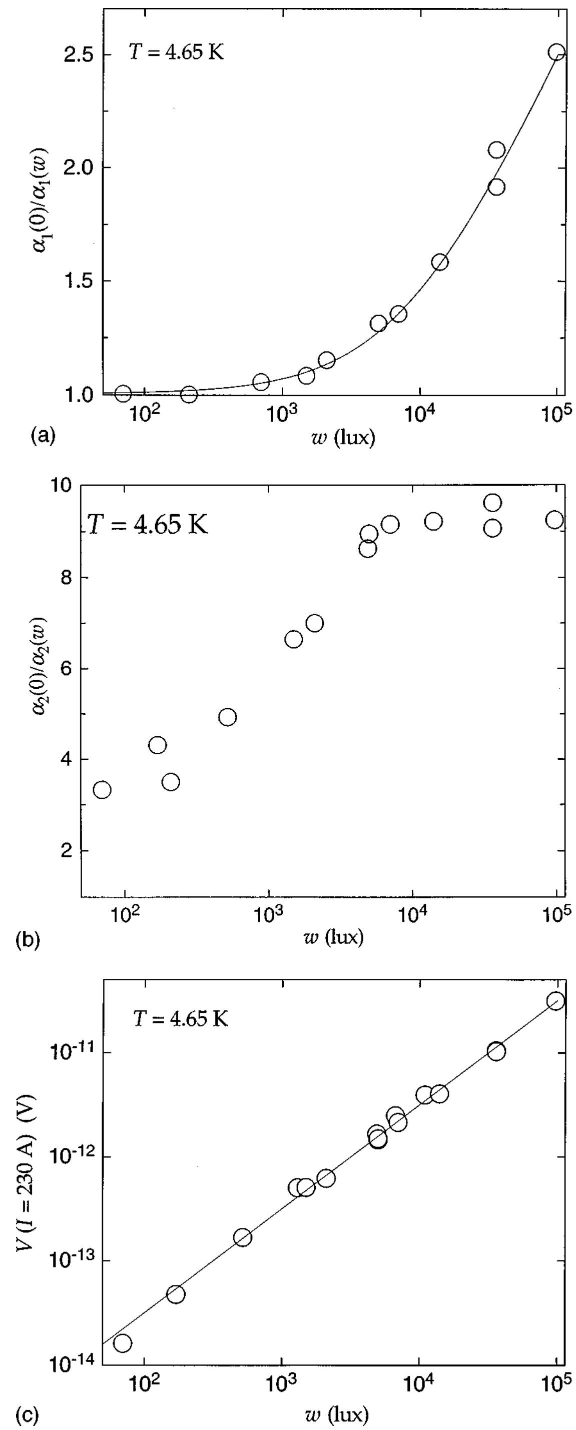

FIG. 5. The ratios (a) $\alpha_1(0)/\alpha_1(w)$ (solid line is a guide to the eyes), (b) $\alpha_2(0)/\alpha_2(w)$, and (c) the voltage at $I = 230$ A (the solid line is a best fit by $V = aw$) as functions of illumination.

where V_0 is a constant, which includes the attempt frequency, the hopping distance, and the magnetic induction. Equation (4) shows that the $\ln V$ versus I curves at constant temperature reflect the current dependence of the activation energy.

At low temperatures the hopping probability is negligible at low currents and hence the flux motion can be observed only at high enough currents. The electrical current creates the Lorentz force acting on vortex bundles, which may be written (per unit of length) as

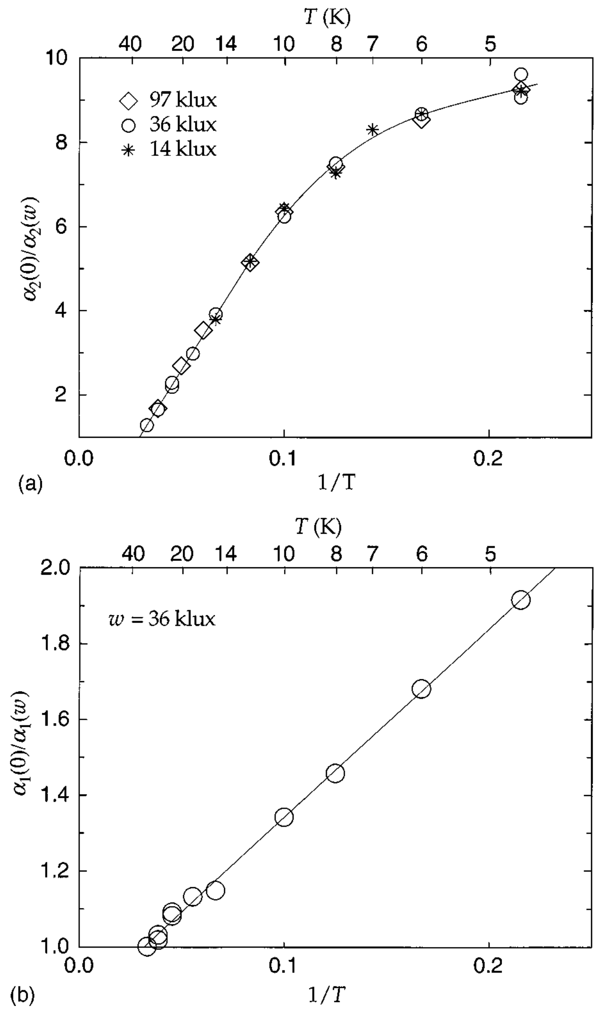

FIG. 6. The ratios (a) $\alpha_2(0)/\alpha_2(w)$ and (b) $\alpha_1(0)/\alpha_1(w)$ versus inverse temperature (solid lines are guides to the eyes).

$$F_L = j\,\frac{m_b \Phi_0}{c}. \tag{5}$$

Here c is the velocity of light, m_b is the number of the vortex lines in the bundle and $\Phi_0 \approx 2\times10^{-7}$ G cm^2 is the flux quantum. To simplify the notation in this and the following sections we shall use the current density j instead of I. As illustrated in Fig. 7(c), the Lorentz force weakens the potential barriers for the vortex motion in one direction and enhances them in the opposite direction. For a nonzero current density we can write $u(x)$ as

$$u(x,j) = u(x,0) - xF_L = u(x,0) - j\,\frac{m_b \Phi_0}{c}\,x, \tag{6}$$

where $u(x,0)$ is $u(x)$ for $j=0$. The coordinates $x_{\min}$ and $x_{\max}$ denote values of x where $u(x,j)$ has its local minima and maxima, respectively. The activation energy $U(j)$ is the difference between two consecutive values of $u(x,j)$ at $x_{\min}$ and $x_{\max}$ along the direction of flux motion. By using Eq. (6) we can write

$$U(j) = u(x_{\max},0) - u(x_{\min},0) - j\,\frac{m_b \Phi_0}{c}\,\Delta x, \tag{7}$$

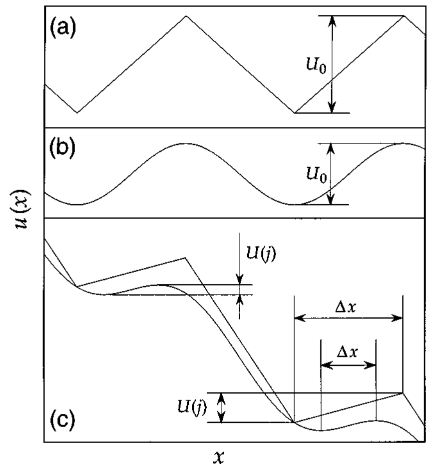

FIG. 7. Two possible shapes of potential barriers. (a) Triangular barriers for $j=0$. (b) Sinusoidal barriers $u(x) = (U_0/2)\sin x$ for $j=0$. (c) Same barriers for $j = 0.7 j_c$.

where $\Delta x = x_{\max} - x_{\min}$. The critical current corresponds to $U(j_c)=0$, which implies that

$$j_c = \frac{c}{m_b \Phi_0}\,u'_{\max}, \tag{8}$$

where $u'_{\max}$ is the maximum value of $du(x)/dx$ calculated for $j=0$. Although the amplitudes U_0 for the two barriers shown in Fig. 7(a) and Fig. 7(b) are different, both of them have the same value for $u'_{\max}$ and hence the same critical current.

In the original paper of Anderson[32] only the simplest case of a linear $U(j)$ dependence was considered. This case corresponds to Δx being independent of the current. However, this is only the case for some particular shapes of potential barriers. For instance, for triangular-shaped barriers, Δx is indeed independent of current [see Fig. 7(a) and Fig. 7(c)] and, according to Eq. (7), the activation energy $U(j)$ is proportional to $(j_c - j)$. In the case of more realistic shapes of potential barriers, Δx depends on the current and $U(j)$ is not exactly a linear function of j. For nontriangular potentials the distance Δx tends to 0 as $j \to j_c$ [see Fig. 7(c)], rendering the dependence of U on $(j_c - j)$ stronger than linear. This is the universal behavior for all types of barriers, for which $d^2u(x)/dx^2$ is a continuous function of x.[38] For this aspect it is not important whether the moving flux object is an individual vortex line or the motion is that of bundles of vortices. According to Eq. (4) this nonlinearity of $U(j)$ should result in a negative curvature of the $\ln V$ versus I curves. This conclusion agrees well with the experimental results for the nonilluminated sample as presented in Figs. 2(a)–2(c). There are more complicated theories of flux creep in HTSC's than the simplest case that we have considered here (see Refs. 35, 36). However, all of them predict negative curvatures for $\ln V$ versus I curves.

Hence we generally expect that for any shape of potential barriers, the V-I curves plotted as $\ln V$ versus I are either straight lines or exhibit some negative curvature. This also means that the pronounced positive curvature observed in the $\ln V$ versus I curves for the illuminated sample [see Figs. 2(a)–2(c)] cannot be attributed to a simple change of the

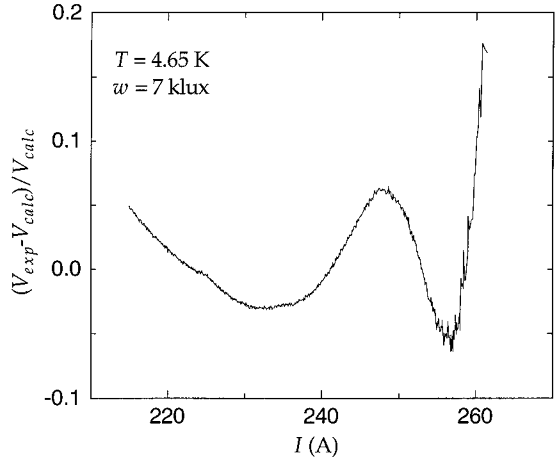

FIG. 8. The normalized difference between one of the measured V-I characteristics (V_{exp}) and the best linear fit using Eq. (9) (V_{calc}).

shape of the potential barriers under illumination. Instead we have to assume that some other mechanism enhancing the flux mobility is activated by illumination. This mechanism is to be dominant at low currents and should provide a flux creep rate, which is proportional to the intensity of illumination [see Fig. 5(c)]. At higher currents the dominant flux-creep mechanism is similar to that, which is also present without illumination. In this situation a slight modification of the potential barriers by illumination may have to be taken into account [see Fig. 2(a) and 2(b)]. In total two mechanisms contribute to the motion of vortices leading to V-I characteristics, which can be approximated by a sum of two exponential terms

$$V = A_1 \exp[\alpha_1(w)I] + A_2 \exp[\alpha_2(w)I]. \tag{9}$$

Figure 8 shows the normalized difference between one of the V-I curves and the best fit using Eq. (9). The maximum discrepancy is typically of the order of 5%, about the same as when the V-I curves recorded without illumination are fitted with a single exponential.

The most effective type of interaction between light and superconductors is the breaking of Cooper pairs by photons and it has been considered as the main mechanism for the non-bolometric photoresponse of HTSC's in almost all the papers on this subject. This process directly transfers the photon energy to the electronic subsystem of the sample and we believe that it is also responsible for the effect we discuss here. In Ref. 31 it was pointed out that, because the number of normal excitations in HTSC's at low temperatures is small, the recombination rate of these nonequilibrium excitations into Cooper pairs in the superconducting regions should be low because of the low probability for 2 excitations to interact in the proper way. At the same time, the density of normal excitations is much higher in the vortex core regions and the recombination process may be expected to be much faster there. Therefore we argue that the non-equilibrium normal excitations, which are created across the illuminated surface of the sample, recombine mainly in the vortex cores, significantly influencing the vortex properties.

Since we are not aware of any model describing the effect of illumination on flux creep we present and qualitatively discuss below two different scenarios that may explain the experimental V-I curves. We consider only the results obtained at the lowest temperatures where the illumination effect is particularly strong. We note that these two scenarios are described in a purely phenomenological manner without considering the microscopic processes that might cause them.

V. EXCITATION OF THE VORTEX SYSTEM BY PHOTONS

As is shown in Fig. 5(c) the flux-creep rate, measured by the voltage around the ring in the low current limit at low temperatures, is approximately proportional to the light intensity. Therefore it may be conjectured that the photons directly affect the flux-creep process. For instance, incident photons can transfer their energy to the vortex system of the sample. In the following we consider how such a process can change the flux-creep rate. We assume that the illumination does not change the activation energy for the flux motion, but changes the energy distribution of the vortices.

The voltage around the ring can be written as

$$V = -\frac{1}{c}\Phi_0 N m_b, \tag{10}$$

where N is the number of flux bundles crossing the ring per second, i.e., N denotes the number of bundles, which energies $\varepsilon > U(I)$. Using Eq. (10), the density of flux bundles per energy interval at $\varepsilon = U$ can be written as

$$n(U) = \frac{dN(U)}{dU} = -\frac{c}{m_b\Phi_0}\frac{dV}{dU} = -\frac{c}{m_b\Phi_0}\frac{dV}{dI}\left(\frac{dU}{dI}\right)^{-1}. \tag{11}$$

The derivative dU/dI can be calculated by using Eq. (4), which relates the activation energy and the voltage. According to Fig. 2(a), the V-I characteristics without illumination may be approximated by $\ln V \approx \alpha I + B$. The constants α and B can be found by fitting the experimental V-I curves for the non-illuminated sample. The parameter α adopts values between those of $\alpha_1(0)$ and $\alpha_2(0)$ introduced earlier (see Fig. 4). Since we are only interested in qualitative features, we neglect the deviations of $\ln V(I)$ from linear behavior. In this case Eq. (4) gives

$$\frac{U}{kT} = (\ln V_0 - B) - \alpha I \tag{12}$$

and

$$\frac{dU}{dI} = kT\alpha. \tag{13}$$

Substituting this expression for dU/dI into Eq. (11) and evaluating dV/dI from Eq. (9), we finally get

$$n(\varepsilon) = \frac{c}{m_b\Phi_0}\frac{1}{kT}\left[C_1\frac{\alpha_1(w)}{\alpha}\exp\left(-\frac{\alpha_1(w)}{\alpha}\frac{\varepsilon}{kT}\right) + C_2\frac{\alpha_2(w)}{\alpha}\exp\left(-\frac{\alpha_2(w)}{\alpha}\frac{\varepsilon}{kT}\right)\right], \tag{14}$$

where

$$C_i = A_i \exp\left[(\ln V_0 - B)\frac{\alpha_i(w)}{\alpha}\right], \quad i=1,2. \qquad (15)$$

Equation (14) shows that, to ascribe the effect of illumination on the flux creep to the excitation of the vortex system, one has to postulate a very specific energy distribution in the system of flux bundles. There are two distinct groups of flux bundles with Boltzman-like distributions, but with very different effective temperatures. The effective temperature for one of the group $T_2^{\text{eff}} = T\alpha/\alpha_2(w)$ is almost an order of magnitude higher than the bath temperature and practically does not depend on the intensity of illumination [see Fig. 5(b)]. For the other group $T_1^{\text{eff}} = T\alpha/\alpha_1(w)$ is much lower than T_2^{eff} and depends much stronger on w [see Fig. 5(a)].

It should be noted that the flux creep without illumination at liquid helium temperatures is due to quantum tunneling rather than thermal activation.[31] However, this does not significantly change the above discussion because it seems quite likely that the excitation of the vortex system by illumination facilitates the hopping of flux bundles over potential barriers, thereby reducing the importance of quantum tunneling.

VI. INFLUENCE OF ILLUMINATION ON THE VORTEX-VORTEX INTERACTION

In this section we consider the situation where the illumination enhances the flux mobility in a different way. As shown in Fig. 2 the main effect of illumination on the V-I characteristics is obviously a substantial decrease of $d \ln V/dI$ with decreasing current. Since, according to Eq. (4), the activation energy U is proportional to $\ln V$, we may quite generally conclude that the illumination decreases dU/dI (or dU/dj). Since Eq. (7) shows that dU/dj is proportional to the product $m_b \Delta x$, a reduction of dU/dj simply requires a reduction of the number of vortices in the vortex bundle.[39]

Without illumination, the activation energy U_1 for a single-vortex hopping exceeds that for moving vortex bundles U_b, rendering single-vortex creep unobservable. Our assumption is that the illumination changes the interaction between vortices in such a way that it decreases U_1 and, as a result, single-vortex hopping also contributes to the flux creep.[40] In this case we have two hopping processes with different activation energies and the voltage can be written as

$$V = V_{01} \exp\left[-\frac{U_1(j)}{kT}\right] + V_{0b} \exp\left[-\frac{U_b(j)}{kT}\right], \qquad (16)$$

where V_{01} and V_{0b} are constants with the same meaning as V_0 in Eq. (4). This expression, which is practically identical to Eq. (9), leads to V-I characteristics very similar to those observed experimentally. This argument does not depend on the particular nature of the flux creep and it is equally applicable considering the thermal activation as well as quantum tunneling. In the latter case U_1/kT and U_b/kT should be replaced by Euclidian actions of the corresponding tunneling processes.

It is interesting to note that $\alpha_2(w) = d \ln V/dI$ is independent of the illumination intensity w between 5 and 100 klux [see Fig. 5(b)]. In this approach this means that neither m_b nor Δx depend on the light intensity in this range of w. The increase of $\alpha_2(w)$ at weaker intensities might then be due to a variation of Δx with illumination in this range of w.

Here we have postulated that the illumination changes the interaction between vortices in a way as to decrease the activation energy for single-vortex hopping. However, it is not clear what kind of mechanism might be responsible for this to occur.

VII. SUMMARY AND CONCLUSION

The influence of illumination with visible light on the flux creep in the mixed state of an epitaxial YBCO film has been investigated in a wide range of temperatures and light intensities. Without illumination, the V-I characteristics plotted as $\ln V$ versus I are almost straight lines. Illumination substantially alters the shape of the V-I curves at low voltages. Applying a light intensity w of a few klux decreases the derivative $d \ln V/dI$ by almost an order of magnitude. In the intensity range $5\,\text{klux} < w < 100\,\text{klux}$, $d \ln V/dI$ is independent of w. The effect of illumination decreases with increasing temperature and it disappears at $T \approx 35\,\text{K}$, well below the superconducting transition temperature $T_c \approx 92\,\text{K}$ of our sample.

We propose two different models, which qualitatively reproduce the experimental V-I characteristics. The first one considers an excitation of the vortex system by photons. The second assumes that the illumination alters the number of flux lines in a moving flux bundle. Both models have many unknown parameters and they provide the same type of V-I characteristics. At present we do not have arguments in favor of one or the other model. Additional experimental as well as theoretical studies seem necessary to further clarify the situation.

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[37] The temperature dependencies of the flux-creep rates without illumination will be considered in more detail elsewhere.
[38] This nonlinearity was pointed out in Ref. 34.
[39] It is difficult to imagine that Δx can be changed by an order of magnitude, which is necessary to explain the experimental results, keeping m_b constant. At the same time, the change in m_b should be accompanied by a change of Δx, which can be significant.
[40] For simplicity we consider here a transition to single-vortex hopping.