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Response of high-temperature superconductors to electromagnetic radiation (A Review)

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Nonequilibrium processes resulting from the interaction of high-temperature superconductors with electromagnetic radiation are considered from microwave to optical range. Emphasis is laid on the dependence of surface or dc resistance on external parameters (temperature, bias current, modulation frequency, magnetic field, radiation power, and frequency), which is characteristic of every nonbolometric response mechanism considered by us. The most frequently used methods for monitoring the response of HTSC to electromagnetic radiation are described. © *1998 American Institute of Physics.* [S1063-777X(98)00105-4]

INTRODUCTION

A high superconducting transition temperature T_c (>77.3 K) together with a small coherence length ξ and a strong anisotropy are responsible for diverse and unusual electromagnetic properties of HTSC as compared to conventional superconductors. Among other things, the concept of vortex lattice and of the shape and dynamics of the vortices themselves have been revised significantly (see, for example, the review by Blatter *et al.*[1]) The transformation of magnetic vortices and the peculiarities of their mutual interaction associated with a strong anisotropy and fluctuational effects have led to various phase transitions and new states of the vortex lattice, e.g., lattice fusion, thermally induced depinning, collective flux creep, and $2D-3D$ transition. All these peculiarities call for a detailed and thorough analysis of the electromagnetic properties of HTSC which is interesting not only from a scientific, but also from a technical point of view.[2] For example, one of the most important and relatively simple applications of HTSC is the development of electromagnetic radiation (EMR) detectors. A negligibly small dispersion (for frequencies $\nu \leqslant 2\Delta/\hbar$, 2Δ being the band gap in the quasiparticle spectrum), steepness of the HTSC transition, and the use of a cheap coolant (liquid nitrogen) urged scientists to explore the possibility of creating HTSC bolometers working at liquid nitrogen temperature.[3,4] The main drawback of such devices is that a compromise has to be sought between sensitivity and high-speed response. Hence it is preferable to use nonbolometric detectors. In this connection, the study of nonequilibrium mechanisms for monitoring the response of HTSC to EMR assumes a special significance. By response we mean the variation of a certain characteristic of the material under the effect of an external agency (in the present work, we shall take for such a characteristic the resistance R of the sample exposed to EMR).

In the general form, the response mechanisms can be divided into two large groups covering bolometric (equilibrium) and nonbolometric (nonequilibrium) response. The bolometric mechanism is one of the most thoroughly investigated mechanisms[4] and hence we shall not consider it in the present work.

In recent publications devoted to the study of optical response[5–8] of microbridges made of epitaxial YBaCuO films, it is assumed that nonbolometric mechanisms are realized not only in granular samples, but also in high-quality HTSC. However, the controversy in the observed values of sensitivity and response time for the same nonthermal mechanisms has not been resolved so far. Most probably, it is linked not with the intrinsic properties of HTSC, but with various external conditions (temperature, bias current, magnetic field, radiation power, wavelength, pulse duration, etc.) under which these characteristics are obtained.[9] In this connection, it is necessary to study nonbolometric mechanisms in samples of the same quality under identical external conditions, and to investigate the conditions for optimizing the characteristics of detectors.

In this communication, we present a review of the most typical results on the investigation of nonequilibrium mechanisms of the response of HTSC to EMR, and systematize the existing mechanisms from the point of view of the most general physical effects characterizing superconductors. We shall not consider in this review the results of investigations in the fields of Raman scattering, generation of harmonics of the fundamental signal, photoluminescence, etc.

The review consists of the following parts. Typical methods for monitoring the response to EMR from the microwave (MW) to optical range are described in Sec. 1. Section 2 is devoted to a review of experimental works on the nonbolometric response mechanisms in HTSC, and to their classification into subgroups. The main results obtained in this field are summarized at the end of the review.

1. METHODS OF RESPONSE MONITORING

In response monitoring, it is important to take into consideration the frequency of the incident radiation and the technique used for monitoring. The former determines the processes induced by the incident radiation, and the latter

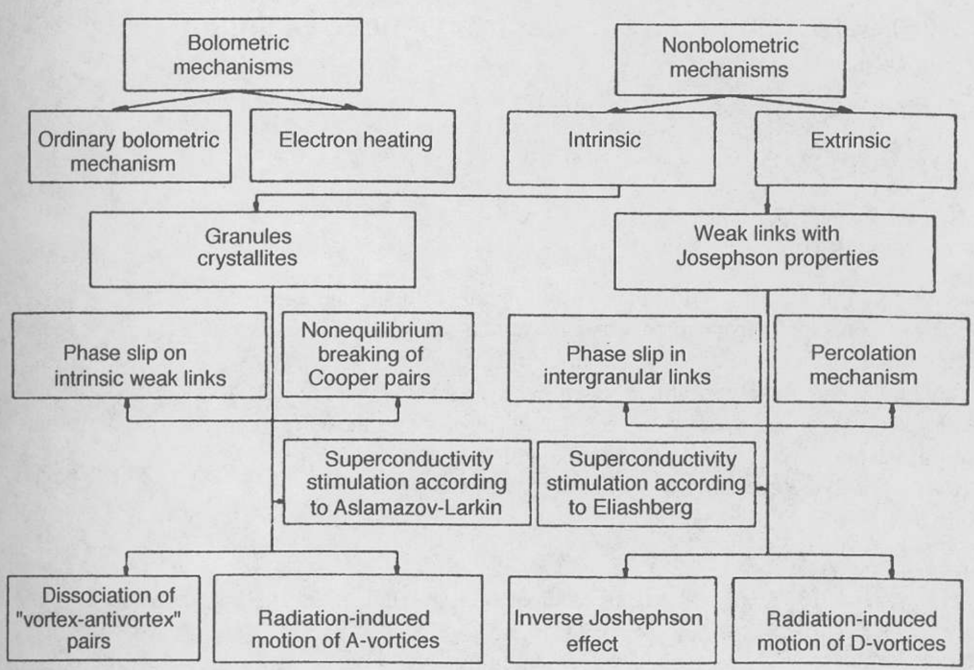

FIG. 1. Mechanisms of electromagnetic radiation monitoring by superconductors.

indicates the processes that may be discovered. The response is conventionally measured in direct current. In spite of the high sensitivity associated with the steepness of the superconducting transition in dc measurements, this method has a number of significant drawbacks. In the first place, special restrictions are imposed on the sample geometry: the thickness of the HTSC film must be smaller than or of the order of the radiation penetration depth δ. Otherwise, a part of the sample in which the radiation does not penetrate will shunt the layer whose properties have changed under exposure, and no response will be detected. Moreover, since the dc resistance of the sample in the superconducting state is equal to zero, the HTSC sample has to be processed with a view toward creating an element with nonzero resistance. In turn, this restricts the range of mechanisms available for monitoring the response. Besides, significant constraints on the noise characteristics of HTSC detectors are imposed by contact resistances of the order of 1 Ω, which are inescapable in such a detection technique.[10] These drawbacks are eliminated in the rf-technique for monitoring the response, although the sensitivity may decrease in this case due to a less steep superconducting transition and a smaller drop in the rf resistance as compared with the dc resistance. The rf-technique used by us for the first time[11] to monitor the response is based on the inductive technique[12] at radiofrequencies (rf) as well as the resonant technique[13] for measuring the MW response. Obviously, the problems associated with fluctuational noise and the degradation of the HTSC element due to contact phenomena are eliminated during rf monitoring of the response. Moreover, the constraints on sample thickness are less stringent in this case, since the only requirement is the overlapping of the incident radiation and the probing radiation penetration regions. Finally, the rf-technique for monitoring the response allows the detection of nonequilibrium processes even in the superconducting transition region, while a large value of the contact resistance and strong nonlinear effects associated with a constant measuring current lead to thermal instability and an ''avalanche''-type crossover to the bolometric regime.

Another effective method of studying the optical response of HTSC is the pump-probe technique[14,15] based on the use of the same agency (usually, a laser) as the source of radiation incident on the sample, and for monitoring the response by measuring the reflectivity of the probing signal. In this case, the nonequilibrium processes can be monitored over a wide range of wavelengths (from 10 μm to ultraviolet). The measuring signal is usually much weaker and is delayed relative to the pumping signal. The resolving power of such a technique is determined by the minimum possible duration of the laser pulse. For an optimal construction of the sensitive element, the amplitude of the nonthermal component is higher than the amplitude of the bolometric component at $T > 80$ K by an order of magnitude.[6]

2. CLASSIFICATION OF RESPONSE MECHANISMS

We are not aware of any classification for the mechanisms of HTSC response to EMR showing their mutual relation with the most typical physical phenomena in superconductors. Such a classification is essential for a proper understanding of the processes stimulated in HTSC by the incident radiation. We believe that, while speaking of nonequilibrium response mechanisms, we must indicate clearly whether a particular mechanism is a property of the given sample or a common feature of the entire class of HTSC. In this respect, all nonbolometric response mechanisms can be divided into two groups, viz., intrinsic and extrinsic (see block diagram in Fig. 1). The intrinsic properties of HTSC are determined by the quality of single crystals and granules (for granular samples). At present, it is assumed that weak links between granules act as a chain of series- and parallel-connected Josephson junctions (JJ) responding synchronously to the incident radiation. Hence the extrinsic properties of HTSC are mainly determined by the properties of a solitary JJ. Apparently, the intrinsic properties of HTSC are mainly similar to the properties of low-temperature type II superconductors with some differences associated with the peculiarities of the HTSC structure. Each of the above-mentioned large categories contains several mechanisms that are common to both groups.

2.1. Radiation-induced creep and flow of magnetic flux

The idea of thermally induced creep was put forth by Anderson,[16] while Zel'dov *et al.*[17] and Frenkel *et al.*[18] were among the first to detect the motion of magnetic flux induced in HTSC by radiation. Zel'dov *et al.*[17] studied the response of microbridges made of epitaxial YBaCuO films on $LaGaO_3$ and $SrTiO_3$ substrates to optical radiation (He–Ne laser, wavelength $\Lambda = 633$ nm), and found that the peak on the temperature dependence of the response is displaced by several degrees towards lower temperatures relative to the dR/dT peak characterizing the bolometric response. They also noticed a significant suppression of the response ΔR with increasing bias current, which was not observed in the temperature dependence of dR/dT. Moreover, the quantity $\Delta R/(dR/dT)$ characterizing the heating of the film in a purely bolometric effect increases sharply and has a peak at a temperature slightly lower than the superconducting transition temperature T_c. Since the thermal properties of the substrate, film, or the interface between them should not vary significantly in this temperature range, the authors concluded that the response is of nonbolometric type. Considering a strong correlation between the behavior of transport properties upon irradiation and without radiation, Zel'dov *et al.*[17] interpreted their results as magnetic flux creep induced by optical radiation. A similar interpretation of the results on the measurement of optical response was given by Frenkel *et al.*[18] who reported the observation of photo-induced depinning of magnetic flux. According to Frenkel,[19] the necessary condition for the emergence of flux flow is that the radiation quantum energy $h\nu$ must exceed the activation energy U_0 of the vortex lattice. The author believes that the photon energy is transferred thermally to flux lines, although other mechanisms of energy transfer (for example, the Lorentz force exerted on a vortex by the induced current) cannot be ruled out.

Eideloth[20] observed the response of BiSrCaCuO ceramic bridges and a meander made of epitaxial YBaCuO film on MgO substrate to optical radiation of wavelength $\Lambda = 633$ nm and concluded that his results can also be explained by the model of the photo-induced flux flow (PIFF). Moreover, the results of measurement on the BiSrCaCuO samples are described correctly by the PIFF model as well as the model of JJ network in which phase slip centers (PSC) are formed under the action of light as a vortex moves through the junction. It was also observed[20] that since the value of U_0 in the PIFF model and the energy barrier $2E_c$ in the JJ network model are close, these two mechanisms can be distinguished only by measuring the temperature dependence of the activation energy.

The contribution to the dc resistivity made by thermally activated flux creep in the case of a linear current–voltage characteristic (IVC) of the sample is described by the expression (see, for example, Ref. 21)

$$\rho = \frac{2\nu_0 \Phi_0^2 L_c}{k_B T} \exp(-U_0/k_B T), \tag{1}$$

where ν_0 is the attempt frequency, i.e., characteristic frequency of attempts by vortices to break away from the pinning center ($\sim 10^{12}$ Hz for YBaCuO single crystals), Φ_0 is the magnetic flux quantum, L_c is the coherence length along a flux line or a vortex bundle (which may vary from fractions of d for very thin samples to d for thick samples, d being the film thickness), and the energy $U_0 \sim 2 \cdot 10^5$ K for YBaCuO single crystals at $T \ll T_c$.[21] As a result, we obtain for the pre-exponential factor in formula (1) $\rho_0 = 10^5\ \mu\Omega \cdot$cm. Note that formula (1) is in good agreement with the experiment for $\rho < 10^{-2}\rho_n$, where ρ_n is the resistivity in the normal state. For $\rho > 10^{-2}\rho_n$, an excellent agreement is obtained with Tinkham's theory[22] in which it is assumed that resistance, which is associated with flux creep, depends on U_0 in the same way as in the case of dissipation due to thermally induced phase slip in a JJ suppressed strongly by the transport current. According to the Ambegaokar-Halperin theory,[23] the JJ resistance in a strongly suppressed state has the form

$$\rho/\rho_n = [I_0(\gamma_0/2)]^{-2}, \tag{2}$$

where I_0 is the modified Bessel function, and $\gamma_0 = U_0/k_B T$. The following dependence on temperature and magnetic field H is proposed for U_0:

$$U_0 \propto \frac{(1 - T/T_c)^{3/2}}{H}. \tag{3}$$

Palstra *et al.*[21] reported that the dependence (3) is valid only over a limited temperature range, and a different temperature- and magnetic field dependence for U_0 obtained, for example, in the vortex glass model[24,25] or the thermally activated flow model,[26] cannot be ruled out.

If the Lorentz force F_L exerted on vortices by the transport current flowing through the sample is such that they acquire an energy $U_L = U_0$, depinning of vortices and a transition to the flux flow regime take place.[27] According to the Bardeen–Stefan theory,[27] the flux flow resistance is described by the expression

$$\rho_{ff} = \rho_n H / H_{c2}, \tag{4}$$

where H_{c2} is the upper critical field.

As regards the rf response associated with the flux flow, it was shown by Ji *et al.*[28] that at temperatures not very close to T_c and for $h\nu \ll 2\Delta$, the specific impedance taking into account the contribution from flux flow can be presented in the form

$$\rho = \frac{\Phi_0 B_{\mathrm{eff}}}{\eta c^2} + \frac{4\pi\omega\lambda_L^2}{c^2}, \tag{5}$$

where η is the viscosity, $\omega = 2\pi\nu$ the angular frequency, λ_L the field penetration depth, and B_{eff} the effective magnetic flux density responding to the rf field. According to Portis *et al.*,[29] the surface resistance taking vortex dissipation into account can be represented in the form

$$R_s = X_0 \left[\frac{-1+(1+4B_{\mathrm{eff}}^2/B_0^2)^{1/2}}{2} \right]^{1/2}, \tag{6}$$

where $X_0 = 4\pi\omega\lambda_L^2/c^2$ is the surface reactance for $B_{\mathrm{eff}}=0$, and $B_0 = 8\pi\omega\eta\lambda_L^2/\Phi_0$ is the characteristic value of B_{eff} for which the surface impedance Z_s is defined by the vortex movement. It was assumed by Portis *et al.*[29] that $B_{\mathrm{eff}} = fH$, where f is the density of free or weakly pinned fluxons ($f \sim 0.1$). However, Ji *et al.*[28] interpreted f as a part of the length of all vortices intersecting the intergranular region in the sample. They assume that there exist intergranular vortices having a number density n_J which do not pass through granules, and intragranular vortices having a number density n_g which are pinned inside granules. Besides, the main contribution to dissipation comes only from vortices intersecting weak links since the viscosity η_J of intergranular region is much higher than that of intragranular regions η_g due to a higher resistance of the intergranular regions. According to Ji *et al.*,[28] $B_{\mathrm{eff}} = (n_J + x n_g)\Phi_0$, where x is the ratio of the intergranular volume to the total volume of the sample.

The method of contactless monitoring of the HTSC response to millimeter (mm) waves was developed by our group in the beginning of 1990's (see Refs. 11 and 30). The technique is based on monitoring using rf bias whose advantages over conventional four-probe technique were known long before the discovery of HTSC.[31] Medvedev *et al.*[31] showed that the use of rf bias increases the sensitivity of detectors and improves their noise characteristics. This method makes it possible to monitor the response simultaneously in two frequency ranges, viz., rf (~10 MHz) by including a superimposed inductance coil in the resonance circuit of the quality-factor meter, and the mm range (~36 GHz) by using a quasioptical dielectric resonator which is also used for supplying a powerful mm-range signal. Details of the experimental technique are described in Refs. 30 and 32.

Investigations of the rf response of ceramic and thin-film samples of YBaCuO to mm radiation show[30,32,33] that, in the superconducting transition region, the response is complex and contains bolometric and nonbolometric components. It was found that the peak of the overall response is displaced relative to the peak of the temperature derivative dR_s/dT of the surface resistance, which describes the purely bolometric effect, by 0.4–0.7 K, depending on the quality of the sample. The displacement of peaks on the temperature scale was reduced by improving the electromagnetic characteristics of the samples (by decreasing R_s and reducing the transition width ΔT). Measurements of the relaxation response after switching off the mm wave pumping radiation[32,33] show a good agreement with various theoretical models describing the relaxation of magnetization of superconductors in the magnetic flux creep regime. The activation energy $U_0 = 0.05$–0.5 eV obtained from our measurements in the temperature range 77–86 K are in reasonable agreement with the experimental results presented in Refs. 28 and 34. Finally the

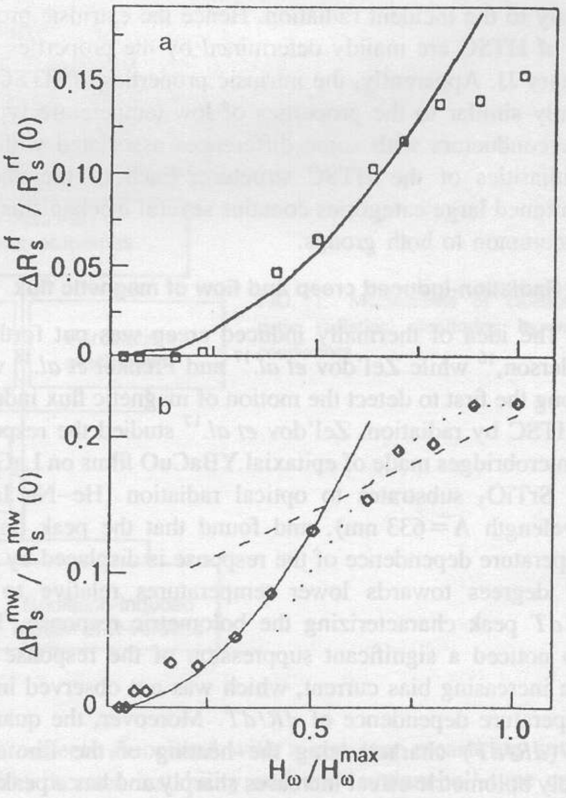

FIG. 2. Magnetic-field dependences of normalized responses of a YBaCuO thin film TF1 at $T=86.7$ K: radiofrequency response $\Delta R_s^{\mathrm{rf}}/R_s^{\mathrm{rf}}(0)$ (*a*) and microwave response $\Delta R_s^{\mathrm{mw}}/R_s^{\mathrm{mw}}(0)$ (*b*). Solid curves describe the approximation according to the Halbritter theory[35] (from Velichko *et al.*[32]).

amplitude dependences of the response of YBaCuO samples of various qualities are also described quite well by theoretical models taking into account the formation and movement of magnetic vortices under the action of a strong rf radiation.[35–37] Figures 2 and 3 show the amplitude dependences of rf and MW response of two thin films of YBaCuO deposited on a $LaAlO_3$ substrate and a YBaCuO ceramic plate, as well as the theoretical dependences obtained by using the models proposed by Halbritter,[35] Sridhar[36] and Gurevich,[37] which are in good agreement with the experimental results. Thus, it can be assumed on the basis of the results of measurements that the rf response of YBaCuO superconductors contains a nonbolometric component in the superconducting transition region. In all probability, the nonequilibrium response mechanism is associated with the creation and movement of Josephson vortices or similar magnetic vortices in inter- and intragranular weak couplings under the effect of millimeter radiation.

Salient features and conditions for realization of the mechanism

(1) The contribution to the dc resistance from the vortex movement is described by formulas (1) (in the case of creep), (4) (for flux flow), and (5) for rf R_s.

(2) The flux creep regime is characterized by an exponential temperature dependence of the resistance (see formula (1)).

(3) The flux creep regime is characterized by a linear IVC for bias currents I satisfying the condition $IHV_c r_p$

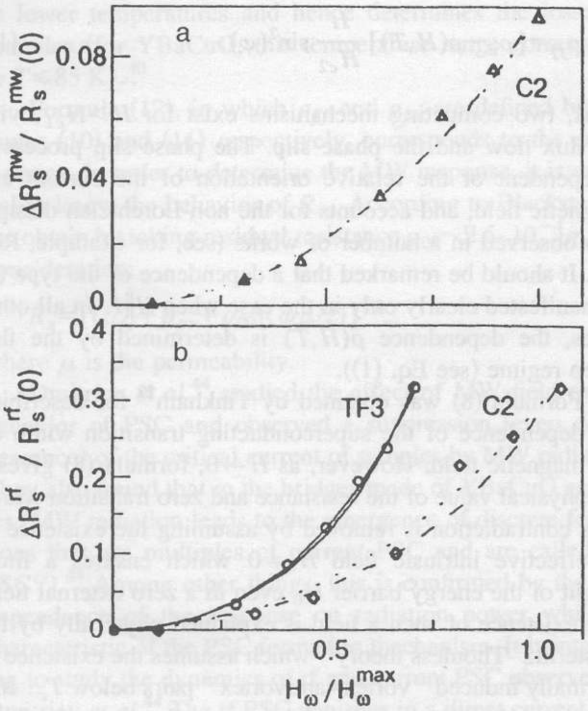

FIG. 3. Magnetic field dependence of the normalized microwave response $\Delta R_s^{mw}/R_s^{mw}(0)$ for a YBaCuO ceramic plate C2 (a) and radiofrequency response $\Delta R_s^{rf}/R_s^{rf}(0)$ for C2 ceramics and thin film TF3 (b) for 86.1 K $<T<$90.5 K. Solid and dotted curves correspond to the approximation according to Gurevich[34] and Sridhar[36] (from Velichko *et al.*[30]).

$\leqslant k_B T$ (V_c is the correlation volume and r_p is the pinning potential range), and by an exponential $V(I)$ dependence for large currents.

(4) The magnetic field dependence of resistance is described by formula (2) and is determined by the magnetic field dependence (3) of the activation energy.

(5) The response amplitude ΔR is proportional to $f_{\rm mod}^{1/2}$, where $f_{\rm mod}$ is the modulation frequency of the radiation.

(6) The flux flow regime is characterized by a linear magnetic field dependence (see formula (4)) and a linear IVC ($V \approx I$).

2.2. Phase slip

A special resistive state is formed in long and narrow superconducting channels [transverse size of the channel $d_c < \xi(T)$], as well as in narrow and even wide thin films for $I > I_c$ both for $I_c = I_c^{\rm GL}$ ($I_c^{\rm GL}$ is the Ginzburg–Landau depairing current) and in an external magnetic field higher than a certain value H_e' ($H_e' = \pi\Phi_0/4w^2$ is the field corresponding to penetration of metastable vortices into a film, and w is the film width). This state cannot be explained just in terms of a dynamic mixed state (DMS)[38] since for high voltages emerging under these conditions, the vortex velocity $v = V/LB$, where L is the sample length and B the magnetic induction, must be of the order of the Fermi velocity, which is evidently not feasible from a physical point of view. High condensate velocities v_s lead to depairing and the number density n_s of pairs begins to depend on v_s. The dependence of the superconducting current density $J_s(v_s)$ passes through a peak corresponding to $J_c^{\rm GL}$. For $J > J_c^{\rm GL}$, the number of superconducting electrons is not sufficient for the passage of transport current, and in contrast to the static case, the total current now contains the normal component J_n as well. The superconducting state continues to be thermodynamically more advantageous since $n_s(v_m) = (2/3)n_s(0)$ at the peak.

Webb and Warburton (see Ref. 19 in the paper by Dmitrenko[38]) detected in 1968 a regular structure of voltage steps on the IVC of tin whiskers and came to the conclusion that individual resistive centers are formed upon an increase in current. The sample resistance (slope of the IVC) increases after the emergence of each step. Later, Tinkham proposed a model of the resistive center called the phase slip center (PSC). He observed the main features of PSC, viz., the magnitude and constancy of differential resistance, as well as oscillations of J_s with Josephson frequency. The formation of the first PSC takes place in a narrow superconducting channel when the current becomes equal to the depairing current at the weakest spot in the sample. A further increase in current results in the motion of normal electrons, which leads to the emergence of an electric field accelerating the superconducting electrons to critical velocity. In this region, the order parameter ψ vanishes and the entire current is transported only by the normal component. However, the formation of Cooper pairs is advantageous as before, hence ψ emerges once again and a part of the current is transported by the condensate. For each such cycle, the phase difference for wave functions of Cooper pairs from opposite sides of the "weak" region will vary by 2π. Hence this site is called a phase slip center. Its characteristic size is determined by the distance over which ψ pulsates, and amounts to $\sim 2\lambda_E(T)$, where λ_E is the length of the voltage drop region.

For $|\psi| = 0$, this region lies in the normal state, and the electric field penetrates the adjacent superconducting regions to a depth $\sim \lambda_E$. Hence the formation of one PSC leads to the emergence of a resistance $2\rho\lambda_E/S$, where ρ is the resistivity of the material of the filament and S its cross-sectional area. The voltage drop across this resistance is associated only with the normal component $I_n = I - I_s$. Averaging of voltage across one PSC over time (taking into consideration the fact that the total current is constant and independent of time, while the supercurrent I_s pulsates between I_c and 0) gives

$$\bar{V} = 2\lambda_E \rho (I - \beta I_c)/S, \qquad (7)$$

where $\beta \sim 0.5$. This simple formula correctly describes the experimental IVC. A further increase in current leads to the formation of new PSC's since new resistive regions come into play each time.[39]

Dmitrenko *et al.* (see Refs. 18 and 55 in their paper[38]) were the first to observe oscillations of the first derivatives of IVC of wide films in the vicinity of T_c, which were interpreted as analogs of PSC. For an applied magnetic field $H_\perp = 0$, the critical current I_c is close to the depairing current and decreases linearly with H as it increases to a certain value H' after which it oscillates with a period ΔH, while the oscillation amplitude increases with decreasing temperature. The period of these oscillations is associated with the periodic modulation of the screening current of the potential edge barrier which hinders the vortex movement. Such a step structure of IVC of wide films was interpreted as the emergence of phase slip lines (PSL) (see Refs. 57 and 58 in the paper[38]). It was found that the IVC of a vortex-free state of a film of width $w \geqslant \lambda_\perp$ ($\lambda_\perp = 2\lambda^2/d$ is the effective field penetration depth in a film of thickness d) for $H<H'$ is similar to the IVC of a narrow superconducting channel with PSC, as in the case $H_\perp = 0$. However, the emergence and movement of vortices in a film for $H>H'$ does not change qualitatively the character of steps on the IVC. The voltage jump is preceded by a nonlinear region corresponding to DMS. Vortex movement is also a phase slip, since the passage of a single vortex through the film corresponds to a variation of the phase difference at the film edges by 2π. However, the mechanisms of PSC and PSL in wide films are quite different from the vortex mechanism.[38] It turns out that the stringent condition of a "narrow" ($d,w \ll \lambda_\perp$) superconducting channel is not necessary for the formation of a PSC. Moreover, the step structure of IVC of wide films is observed in zero magnetic fields also.

One of the first observations of radiation-induced phase slip in HTSC was reported by Leung *et al.*[10] who studied the optical response of granular YBaCuO films on sapphire substrates. Between T_c (temperature corresponding to zero resistance) and T_{c0} (temperature corresponding to the onset of superconducting transition), most intergranular links become nonsuperconducting, and the dc conductivity is associated with individual isolated channels in which the Josephson coupling is still strong. The size and number of such channels decreases with increasing temperature, and the response amplitude becomes smaller.[10] Obviously, the peak of the response emerges at a temperature at which most of the JJ with almost identical critical parameters (critical current, etc.) change upon exposure to radiation. The dependence of the phase slip resistance on activation energy for strongly suppressed JJ was obtained theoretically by Ambegaokar and Halperin [formula (2) in Ref. 23], and can be presented in the following form if we take into account the temperature and magnetic field dependence of U_0 from the theory developed by Yeshurun and Malozemoff (formula (3) in Ref. 24):

$$\rho_{ps}(H,T)=\rho_n\left[I_0\left(\frac{A_T(1-T/T_c)^{3/2}}{2H}\right)\right]^{-2} \quad (8)$$

where A_T is a coefficient. According to Blackstead *et al.*,[40] the passage of transport current with energy exceeding U_0 for $H>H_{c1}$ (H_{c1} is the lower critical field) causes a flux flow whose resistance is defined by formula (4). However, $\rho_{ff}=\rho_n$ in the vicinity of T_c, and hence the resistance in this region will be double the normal state resistance, which is apparently not possible physically. This can be avoided by making the substitution $\rho_n \rightarrow \rho_n - \rho(H,T)$. This gives

$$\rho_{ff}=[\rho_n-\rho(H,T)]\frac{H}{H_{c2}}. \quad (9)$$

Here, $\rho(H,T)\equiv\rho_{ps}(H,T)$ from formula (8). Taking into consideration the angle φ between the current and the magnetic field in the (**ab**) plane, we obtain[40]

$$\rho_{ff}=[\rho_n-\rho(H,T)]\frac{H}{H_{c2}}\sin^2(\varphi). \quad (10)$$

Thus, two competing mechanisms exist for $H>H_{c1}$, viz., the flux flow and the phase slip. The phase slip process is independent of the relative orientation of the current and magnetic field, and accounts for the non-Lorentzian dissipation observed in a number of works (see, for example, Ref. 41). It should be remarked that a dependence of the type (8) is manifested clearly only in the case when $H\|I$. In all other cases, the dependence $\rho(H,T)$ is determined by the flux creep regime (see Eq. (1)).

Formula (8) was obtained by Tinkham[22] for describing the dependence of the superconducting transition width on the magnetic field. However, as $H\rightarrow 0$, formula (8) gives a nonphysical value of the resistance and zero transition width. This contradiction is removed by assuming the existence of an effective intrinsic field $H_0 \neq 0$ which ensures a finite height of the energy barrier U_0 even in a zero external field. The existence of such a field is explained physically by the Kosterlitz–Thouless theory[42] which assumes the existence of thermally induced "vortex–antivortex" pairs below T_c. It is found that the current-induced depairing of vortex pairs leads to nonohmic losses for $H=0$.[43] Taking such a dependence into account, we can present formula (8) in the form[43]

$$\rho_{ps}(H,T)=\rho_n\left\{I_0\left(\frac{A_T(1-T/T_c)^{3/2}}{2(H+H_0)}\right)\left(1-\frac{I}{I_{c0}}\right)^{3/2}\right\}^{-2}. \quad (11)$$

Typical values of H_0 for high-quality YBaCuO samples are ~0.1–0.25 T, while H_0~0.05 T for BiSrCaCuO.[43] For high-quality YBaCuO single crystals (see Ref. 41), the experimental data for $H=0$ are approximated quite well for $A_T=10.044k_BT$. It is found that the narrower the superconducting transition, the higher the value of A_T. Moreover, the resistance calculated by using formula (11) is quite sensitive to the choice of T_{c0}, and hence a variation of T_{c0} even by 0.05 K strongly affects the value of ρ:

$$\rho=\rho_{ff}+\rho_{ps}. \quad (12)$$

It is also assumed that T_{c0} does not change in an applied magnetic field.

According to Blackstead,[43] the disordered distribution of oxygen in Cu–O planes leads to discontinuities, and a network of JJ parallel to the **c**-axis is formed between overlapping regions of adjacent planes and creates conducting channels between planes. The critical current of the entire channel is determined by the weakest junction. Thermal fluctuations lead to a relative displacement of fragments of the Cu–O planes, and perturbation of vortices pinned at these fragments leads to a time-dependent local phase difference. This results in a field dependence of resistance that is not associated with the Lorentz force.

Thus, in view of the leading role of thermal fluctuations near T_c, the dominating loss mechanism is the phase slip associated with the nanogranular nature of HTSC, i.e., with the thermal-phonon-modulated bonds between planes. According to Blackstead,[43] the resistance to flux flow dominates at lower temperatures and hence determines the losses in granules (for YBaCuO, this temperature range corresponds to $T \leqslant 85$ K).[40]

Formula (12), in which ρ_{ff} and ρ_{ps} are defined by formulas (10) and (11) respectively, corresponds to the dc resistance. In order to determine the MW response, it is essential to know the behavior of R_s. According to Blackstead,[40] we obtain by taking residual resistance $\rho_{00} \sim 2.5 \cdot 10^{-4} \rho_n$ into consideration:

$$R_s = [(\rho_{ff} + \rho_{ps} + \rho_{00})(\omega\mu/2)]^{1/2}, \tag{13}$$

where μ is the permeability.

Dmitriev *et al.*[44] studied the effect of MW field on the behavior of PSC and observed a suppression (even disappearance) of the critical current of samples by MW radiation. They also found that in the bridges made of YBaCuO ceramics (MW radiation leads to the emergence of discrete formations that are multiples of current PSC and are called "rf PSC").[44] Among other things, this is confirmed by the root dependence of the response on radiation power which is characteristic of the PSC formation mechanism. It is interesting to study the dynamics of rf and current PSC observed by Dmitriev *et al.*[44] The rf PSC vanishes in a direct current, and is replaced by a current PSC. This is accompanied by a transition of the sample to the "unperturbed" resistive state (with zero radiation power $P_\omega = 0$).

Salient features and conditions for realization of the mechanism

(1) The IVC of superconducting channels in which PSC are formed is described by Eq. (7).
(2) The dependence of phase slip resistance on temperature, magnetic field and bias current is described by formula (11). This mechanism is especially clearly manifested for parallel orientation of current and magnetic field along the c-axis since there is no contribution from the flux flow in this case. In view of the thermal activation nature of the process, it is manifested quite strongly in the vicinity of T_c.
(3) The phase slip resistance is independent of the angle between the current and the magnetic field.
(4) The response amplitude increases in proportion to the square root of the radiation power.

2.3. Breaking of "vortex–antivotex" pairs

A large number of publications (see, for example, Ref. 45) report on the nonbolometric detection of infrared (IR) radiation in thin HTSC films. This regime is characterized by an anomalously large responsivity R_v approaching the quantum limit $R_v = 1/(2e\nu)$. In order to explain this effect, Kadin *et al.*[46] proposed a model for photon-induced dissociation of vortex pairs existing in two-dimensional superconductors. The theory of vortices in two-dimensional superconductors[42] assumes the presence of "vortex–antivortex" (V-AV) pairs below T_c which effectively screen vortex interaction at high temperatures and lead to the formation of free vortices. Under the action of transport current, these vortices move and lead to energy dissipation. As the temperature is lowered, most of the vortex pairs "freeze out" and a second phase

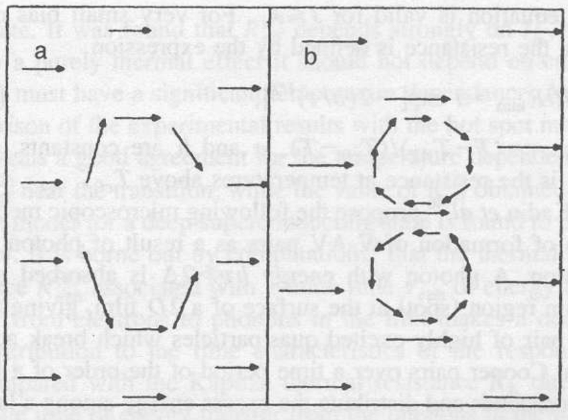

FIG. 4. The pattern of current flow near a "vortex–antivortex" pair generated for a large transport current: total current (a) and the same configuration with separated vortex currents (b) (from Kadin *et al.*[46]).

transition, called Kosterlitz–Thouless transition, occurs at a temperature $T_{\rm KT}$ and is accompanied by a pairing of all free vortices. Below $T_{\rm KT}$, all vortices are paired, and there is no dissipation associated with their movement.[46] The formation of vortex pairs takes place through the emergence of a vortex "core" on the scale of the coherence length ξ with a local suppression of the order parameter ($\Delta = 0$). This may be caused by thermal fluctuations or by the photons of the incident radiation.[47] If vortices are separated in space, i.e., do not overlap, the currents circulating around the core become significant and the vortices are stable. The energy of such a pair, separated by a distance $r \gg \xi$, can be represented in the form[47]

$$E_v = E_{v0} \ln(r/\xi) = \Phi_0^2 d / 2\pi\lambda_L^2 \ln(r/\xi). \tag{14}$$

For two closely-spaced vortices, the minimum energy E_{v0} of the vortex pair is of the order of energy of condensation in two vortex cores. As a rule, this energy is much higher than Δ. The above equation also gives the energy of attraction between vortices which is overcome by the Lorentz force emerging as a result of the passage of a current with density $J = E_{v0}/\Phi_0 r d$. For $r = \xi$, the current density J approaches the critical value J_c, thus indicating that a vortex pair may be formed by current alone. Such a model is a two-dimensional generalization of the model of PSC formation in a superconducting microstrip.[48] Figure 4 shows the current configuration in the vicinity of a vortex-pair being formed. For $T < T_{\rm KT} = E_{v0}/4k_B$, the breaking of the vortex pair may be caused by the current, resulting in a nonlinear IVC of the type $V \approx I^n$. Depending on temperature, three regimes with different IVC can be singled out:

$$V(I) = \begin{cases} \sim (I - I_c)^n, \quad n > 3 & \text{for } T \ll T_{KT}, \quad I > I_c, \\ \sim I^3 & \text{for } T = T_{KT}, \\ \sim I \text{ for } T > T_{KT} & \text{for small } I. \end{cases} \tag{15}$$

Such a form of IVC is caused by thermal activation processes leading to a nonlinear resistance of the form

$$R(J) \sim \exp\left(-\frac{E_v(J)}{2k_B T} \right) \simeq (J/J_c)^{E_{v0}/2k_B T}. \tag{16}$$