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THERMAL DESTRUCTION OF SUPERCONDUCTIVITY OF $YBa_2Cu_3O_{7-x}$ THIN FILMS UNDER VARIOUS CONDITIONS OF HEAT REMOVAL

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The volt-ampere characteristics of thin films of $YBa_2Cu_3O_{7-x}$ with different heat removals from a specimen are experimentally determined. The influence of boiling of liquid nitrogen on the destruction dynamics of the superconducting state in thin HTSC-films loaded with the carrier current is investigated.

In superconductors loaded with a current zones may emerge which are in the normal or resistive states. As a result of Joule self-heating, complete destruction of the superconducting state of the conductor is possible. Thermal destruction of superconductivity is one of the main factors determining stable operation of superconducting systems [1, 2]. The difference in electrophysical and thermophysical parameters of high temperature superconductors in comparison with "classical" low temperature ones as well as different thermal conditions of their operation lead to some peculiarities of cryostabilization of high temperature superconductors. These circumstances refer in full measure to HTSC-films having large values of the critical current density.

In the conditions of self-heating there may emerge a state of thermal multistability of the superconductor when, given the prescribed value of the external controlling parameter (in this case of the carrier current), several stable states exist. With a local character of the superconductor destruction and formation of temperature-electric (resistive) domains, the transition between the stable states is an autowave process of nonisothermal self-sustaining propagation of the phase transition front [1, 2]. Given certain conditions, in the specimen there may arise spatial or time dissipation structures. Investigating the properties of thermal autowaves is of interest from the viewpoint of development of general ideas of the dynamics of nonlinear processes in multistable systems.

The works [3, 4] show experimentally the possibility of emergence of thermal bistability in HTSC-films when cooling the specimens by a rarefied gas. In cooling the superconductors directly by a liquid coolant, for example, when immersing in liquid nitrogen, the coefficient of heat transfer from the specimen surface h can no longer be considered constant. The value of h varies substantially with varying temperature head, i.e., the temperature difference between the superconductor surface and the nitrogen bath. The variation in the heat-transfer coefficient is connected with the possibility of transition from the regime of free single-phase convection to nucleate boiling and of transition from nucleate to film boiling (burn-out). The possibility of changing heat-transfer regimes in cooling of the heated HTSC-ceramic by liquid nitrogen is experimentally shown in [5, 6]. The present work investigates experimentally the influence of a change in the regime of heat transfer on the stability of the superconducting state of HTSC-films when the carrier current flows through the specimen.

Experimental Procedure and Results. Thin films of $YBa_2Cu_3O_{7-x}$ were produced by the method of magnetron sputtering on a direct current of the target of a stoichiometric composition on substrates of strontium titanate monocrystals [4]. Use was made of the procedure for producing "in situ" without subsequent high temperature annealing. The critical temperatures of transition to the superconducting state comprised $T_c = 85$-90 K for different specimens with the critical current density $j_c = 10^9$-10^{10} A/m^2 at 77 K. The film thicknesses were 0.1-0.5 μm; the area was ~1 cm^2. On the film surface, bridges ~1 mm wide and ~5 mm long were etched.

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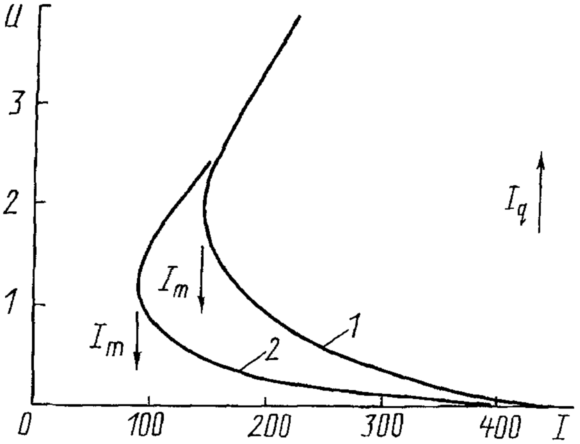


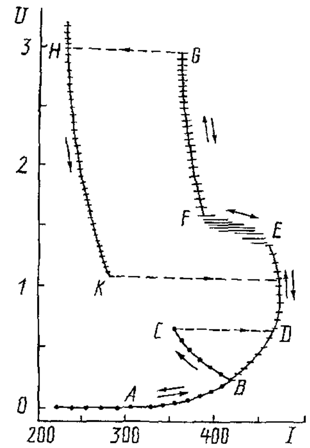


Fig. 1. Volt-ampere characteristics of films in the gas cryostat in various conditions of heat removal: $\alpha = 9.2$ (1) and 19.7 (2). U, V; I, mA.

Fig. 2. Volt-ampere characteristic of the film taken in liquid nitrogen.

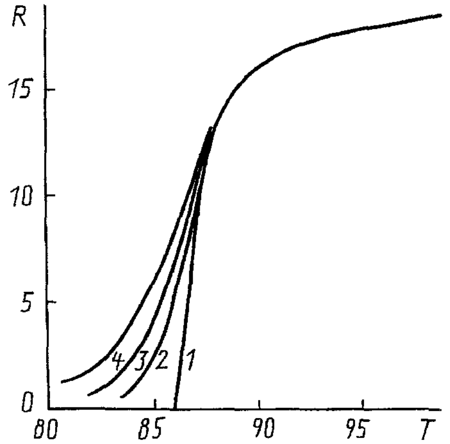
To investigate thermal destruction of the superconducting state, the volt-ampere characteristics (VAC) of the films were determined. The VAC were determined by the standard four-probe method on the direct current. Sprayed two-layer (Ag-In) strips served as terminal areas. The VAC were recorded on an N-307 recorder. Measurements were performed in the regimes of fixation of both the current and the voltage [4]. The regime of voltage fixation enables one to take nonstable sections with negative differential resistance, which are not realizable in the current fixation regime (in the current fixation regime voltage jumps are observed on these sections). Experiments were performed both in a gas cryostat and while directly immersing the films in liquid nitrogen.

Figure 1 gives two volt-ampere characteristics of one of the specimens taken in the gas cryostat under various conditions of heat removal. The heat-removal conditions were determined by the construction of the specimen holder. A more massive copper holder ensured better heat removal from the specimen (curve 1 in Fig. 1). The VAC are taken in the voltage fixation regime [4]. The initial film temperature was the same and comprised 78 K. If in the process of measurements in the voltage fixation regime one goes to the current fixation regime, the system relaxes to one of the stable states - superconducting or normal [4]. It should be remarked that in the experiments with thin-film bridges relaxation to the normal state was often accompanied by specimen burn out.

Figure 2 gives the VAC for one of the specimens immersed directly in liquid nitrogen. With carrier currents larger than the critical one, in the specimen a stable resistive state emerges (section AB in Fig. 2). On further increasing the load in the specimen a structure unstable in the regime of current fixation arises. In the voltage fixation regime on the VAC a section with a negative differential resistance emerges (section BC). Heat transfer with the liquid nitrogen on this section is by single-phase convection. At the point C local boiling of the nitrogen occurs and the system abruptly goes to the point D (along the load curve of the electric circuit). Section DE corresponds to local boiling of the nitrogen at a "weak" place in the specimen. Oscillations caused by separating vapor bubbles were observed on the VAC. On section EF a drastic growth of the oscillation amplitude was observed and random jumps from the point E to the point F (along the load curve) took place. Some increase in the separation diameter of the bubbles was visually observed on this section. At some load (point G) the vapor bubble boundary abruptly moved, with a continuous vapor film being formed on the specimen surface. A reverse transition from film boiling to the nucleate one took place at other loads (point K), i.e., hysteresis was observed on the VAC.

It is noteworthy that the VAC corresponding to the points ABCDEFG were qualitatively reproduced on all investigated specimens, while the transition from nucleate boiling to the film one was not always observed. Besides, as the burn out occurred the HTSC-films often burned, which sometimes was accompanied by mechanical destruction of the substate.

In the nucleate boiling regime, generation of vapor bubbles could occur at two or more "weaker" places in the film, which was reflected on the volt-ampere characteristics. On some specimens the effect of "trigger switch" of the bubbles was observed. A vapor bubble originated first at one "weak" place, disappeared, and emerged at another



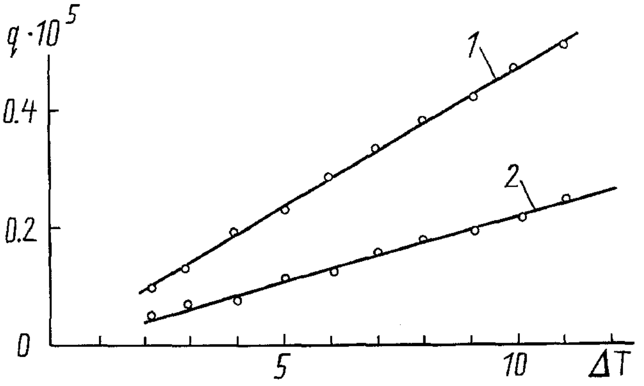


Fig. 3. Temperature dependence of the film resistance at different values of the carrier current I: 1) 25 mA; 2) 100; 3) 300; 4) 500. R, Ω; T, K.

Fig. 4. Density of the heat flux from the film surface vs. temperature head. $q \cdot 10^5$, $W \cdot m^{-2}$; ΔT, K.

"weak" place. After a time the bubble returned to the original place. Visually this was perceived as periodic bubble motion from one place to another and back. The times of bubble jump from one place to another were ~0.1 sec.

To obtain more detailed information on the processes occurring when the carrier current flows through a superconductor, it is necessary to know the temperature on the specimen surface. It is difficult to directly measure the temperature on the thin-film bridge surface, and a variation in the substrate temperature leads to an error connected with the presence of a temperature gradient along the normal to the film surface. The HTSC-film itself served as a temperature sensor in the present work. By virtue of a strong temperature dependence of the electric resistance of the superconductor the film temperature can be determined from the value of its resistance. For this purpose it is necessary to know the temperature dependence of the resistance at operating values of the carrier current R(T, I). Measuring R(T, I) on direct current is possible solely at small values of the carrier current [3], since at large I Joule self-heating emerges, which results in the above difference of the film temperature and the measured thermostat temperature. This problem can be solved by performing measurements of R(T, I) in the pulse regime. Given sufficiently short pulses, the Joule self-heating is insignificant; the film temperature may be considered equal to the thermal platform temperature (in the approximation of a uniform temperature distribution over the film). Such measurements are performed in the present work. For this purpose we developed and manufactured a fast electronically operated current generator which enabled us to produce current pulses of any prescribed shape in the specimen circuit. In the experiments use was made of saw-like and rectangular shapes of the current pulses with a duration of 5-100 μsec and an amplitude to 2 A.

The carrier current pulses and a response from potential contacts were recorded using an S9-8 digital oscillograph. In applying rectangular pulses, by the response shape one may judge the heating of the specimen during the pulse. For pulses with a current density ~10^9 A/m^2 noticeable heating (≥ 0.1 K) began at durations above 10 μsec. With smaller current densities noticeable heating was observed correspondingly at longer pulse durations. The film resistance was determined at pulse durations under 10 μsec. Figure 3 shows the temperature dependences of one of the specimens at different values of the carrier current. It should be noted that the results of determining R(T, I) by the pulse method agree within the accuracy of experiment with the results of determining R(T, I) on the direct current at small values of I when Joule self-heating can be ignored. From the dependences R(T, I) obtained for each specimen one can determine the specimen temperature at each point of the volt-ampere characteristic (in the approximation of a uniform temperature distribution along the film).

Discussion of the Results. The temperature field in the specimen is described by the heat-conduction equation

$$c \frac{\partial T}{\partial t} = \frac{\partial}{\partial r} a \frac{\partial T}{\partial r} + Q(T, I) - W(T), \tag{1}$$

where c is the heat capacity; α is the thermal conductivity; Q(T, I) and W(T) are, respectively, the heat liberation and heat removal powers. In the stationary homogeneous case, (1) becomes the condition of heat balance in the system, which will be written as

$$UI = h(T - T_0),$$

where I is the carrier current; U is the voltage drop on the specimen; h is the effective coefficient of heat transfer from the specimen surface; T_0 is the cryostat temperature. This condition is fulfilled, generally speaking, at three values of temperature, two of which correspond to stable states and one to an unstable one, which determines the S-shape of the volt-ampere characteristics [1]. Thermal stability of the superconductor is characterized by the Stekly parameter α, determining the interval width from the current, in which the normal state can be sustained by Joule heat liberation [1]: $\alpha = I^2_q/I^2_m$, where I_q is the minimal current at which the stability of the superconducting state is impaired; I_m is the minimal current of existence of the normal phase. For the volt-ampere characteristics given in Fig. 1 the Stekly parameter is equal to, respectively, 9.2 and 19.7.

In the approximation of a uniform temperature distribution over the film surface, by using the dependences R(T, I) (Fig. 3) one may determine the film temperature corresponding to each point of the VAC. Figure 4 gives the dependences, calculated with the experimental data, of the effective density of the heat flux from the film surface on the temperature head $T - T_0$ for two conditions of heat removal (the same specimen as in Fig. 1). From Fig. 4 it is evident that on cooling the film by a rarefied gas the effective heat-transfer coefficient h is independent of temperature.

Boiling of liquid nitrogen leads to a substantial difference of the VAC taken in the gas and liquid cryostats.

The section of the VAC corresponding to the single-phase convection regime (section BC in Fig. 2) is qualitatively similar to the VAC taken in the gas cryostat [4]. On this section either a localized resistive domain or a distributed dissipation structure forms, i.e., the alternation of regions which are in the superconducting and resistive (normal) state. The nitrogen superheating close to the surface comprises $\Delta T \approx 10$ K. Nitrogen comes to the boil on the film portion with increased heat liberation whose existence is conditioned by the specimen heterogeneity, the nitrogen superheating being stopped and the effective temperature close to the film surface decreasing (although the local temperature at the boiling point may increase). The nitrogen boiling at a "weak" place contributes to the localization of the resistive domain.

The existence of two "weak" places close in their characteristics may result in the effect of "switch," described above. Electric power fed to the specimen is insufficient for simultaneous generation of vapor bubbles at two "weak" places; therefore the alternation of switches of one or another "weak" place occurs. It should be pointed out that an alternative explanation is also possible, according to which the resistive domain and the vapor bubble following it move as a whole in reconstructing the distributed dissipation structure with localization and "settled life" at "weak places" of the film.

Section EF in Fig. 2 is apparently connected with the peculiarities of the dynamics of the dissipation structure in the specimen. On this section there is strong feedback between the internal dynamic processes in the film and the nonstationary heat removal in nucleate boiling, which leads to a noticeable increase of the oscillations on the VAC.

In the nucleate boiling regime one can no longer ignore the nonuniform temperature distribution over the film. To find such a distribution, the heat-conduction equation (1) with the corresponding boundary conditions is to be solved.

Thus, variation of the heat transfer regime substantially affects the stability of the superconducting state, which should be taken into account in cryostabilization of current-carrying HTSC-systems.

NOTATION

T, temperature, K; R, resistance, Ω; I, electric current, A; U, electric voltage, V; Q, heat liberation power; W, heat removal power; h, effective heat transfer coefficient; q, heat flux density, W/m^2; α, Stekly parameter.

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