Frozen photoconductivity in YBaCuO films

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(Submitted 29 May 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **52**, No. 1, 696–700 (10 July 1990)

The frozen photoconductivity was observed in $YBa_2Cu_3O_{6+x}$ films near the semiconductor-superconductor transition. A broad superconductivity transition near 40 K was observed on the temperature-vs-resistance curve after the films were exposed to a light from an argon laser. The frozen photoconductivity state was retained up to room temperature at which the relaxation time was on the order of 20 h.

The concentration of free carriers is a key parameter which determines the transport, superconducting, magnetic, and structural properties of high-T_c superconducting compounds. The superconducting properties in high-T_c superconductors, for example, appear near the insulator–metal transition.[1] Doping of high-T_c materials is usually accomplished by chemical substitution of the elements, as in the case of $La_{2-x}(Ba,Sr)_xCuO_{4-y}$ (Ref. 1) and $(Pr,Nd,Sm)_{2-x}Ce_xCuO_{4-y}$ (Ref. 2), or by changing the concentration of oxygen in YBa_2O_{6+x} (Refs. 1 and 3). The excitation of electrons to the conduction band—the photoconductivity effect[4]—is another method (one that is not related to the change in the chemical composition of a substance) of changing the concentration of free carriers.

We have observed the phenomenon of frozen photoconductivity in $YBa_2Cu_3O_{6+x}$ films near the insulator–metal transition.

The electrical properties of the $YBa_2Cu_3O_{6+x}$ films can easily be changed by varying the oxygen concentration in the range[1] $0 \leqslant x \leqslant 1$. The compound $YBa_2Cu_3O_6$ is an insulator. An increase in the oxygen concentration gives rise to the appearance of free carriers (holes). At $x = 0.45$ the compound $YBa_2Cu_3O_{6+x}$ undergoes an insulator–metal transition, which is accompanied at low temperatures by a transition to the superconducting state. A further increase in x is accompanied by an increase of T_c to 92 K with $x = 1$. The phase diagram of $YBa_2Cu_3O_{6+x}$ (Ref. 3) is shown in the inset in Fig. 1.

We used $YBa_2Cu_3O_7$ films with a $SrTiO_3$ substrate (6×4 mm in size). The films were fabricated at VNI "Monokrystallreactive," (Kar'kov) by a laser-evaporation method. The c axis of the grown films was oriented at right angles to the substrate. The film thickness was about 1000 Å. Silver contacts, shown in Fig. 1, were deposited on the surface of the films. The use of five contacts [two current contacts (*1* and *5*) and three potential contacts (*2*, *3*, and *4*)] made it possible to measure the resistances of different regions of the film—R_{23} and R_{34}. The $YBa_2Cu_3O_7$ films had a temperature $T_c = 87$ K and the transition width was 1–2 K (Fig. 1).

A fraction of the oxygen was removed from the film by annealing it in vacuum for 10 h at 300 °C. The composition of the film was not monitored independently after the annealing. The temperature dependence of the resistance of the film annealed under these conditions shows, however, that the oxygen concentration is close to the critical

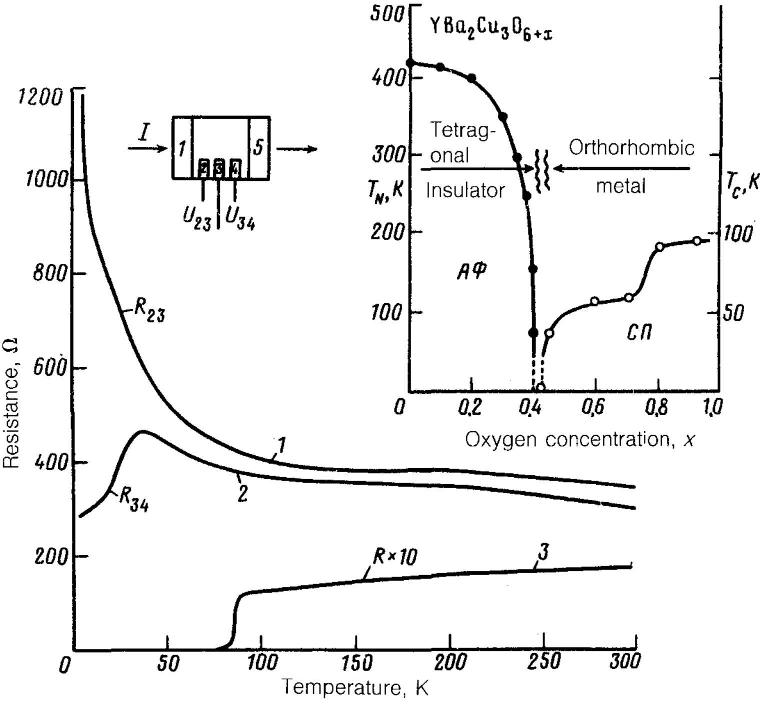

FIG. 1. Temperature dependence of the resistance of YBaCuO film. Curve *1*—Resistance $R_{23}(T)$ and $R_{34}(T)$ of $YBa_2Cu_3O_7$ before the annealing in vacuum; curves *2* and *3*—the same for $YBa_2Cu_3O_{6+x}$, after the annealing. The inset shows the phase diagram of $YBa_2Cu_3O_{6+x}$, taken from Ref. 3 (AP—antiferromagnetic phase; SP—superconducting phase).

concentration, $x \simeq 0.45$, which corresponds to a metal–insulator transition. After annealing, the resistance of the film increased by a factor of approximately 20 at room temperature (Fig. 1). At low temperatures (at which either a localization or superconducting behavior is seen, depending on the composition) we observed an irregularity in the film. The part of the film between contacts *2* and *3*, region R_{23}, behaved like a semiconductor, characterized by a sharp increase of $R_{23}(T)$ with decreasing temperature. In another part of the film (contacts *3* and *4*) we saw small isolated superconducting regions which caused a decrease of the resistance R_{34} below 30 K (we call R_{23} the high-resistance part of the film and R_{34} the low-resistance part). Such a large nonuniformity of the conductivity of an annealed film at low temperatures stems from the fact that $YBa_2Cu_3O_{6+x}$ goes superconducting rather abruptly in terms of the oxygen concentration. As a result, a relatively small change in the oxygen concentration x near the semiconductor–superconductor transition may account for a large variation of the electrical properties at low temperatures.

After the annealing, the films which were immersed into a superfluid helium at $T = 2$ K were bombarded with a 300-mW argon laser (the green line $\lambda = 511.4$ nm). We found that the resistance of the film decreased appreciably after the bombardment. An interruption of the laser light in this case had no effect on the resistance of the sample, which remained constant (the frozen conductivity effect). The resistance of the two parts of the film is plotted in Fig. 2 as a function of the irradiation time. At $T = 2$ K the light-induced change in the resistance differs markedly in the two parts of

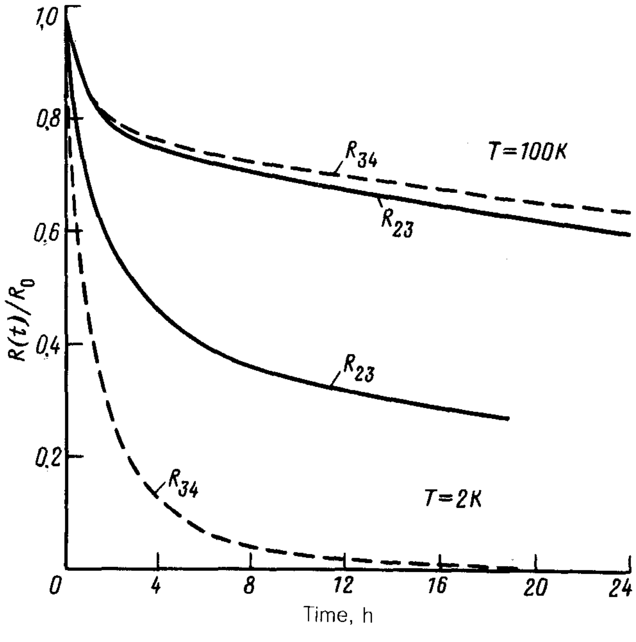

FIG. 2. Resistances of the different parts of the film, R_{23} and R_{34}, vs the bombardment time with an argon laser at two temperatures: 2 K (luminosity 300 mW) and 100 K (200 mW).

the film; the resistance of the high-resistance part of the film, R_{23}, decreases by a factor of four in 20 h, while the resistance of the low-resistance part of the film, R_{34}, decreases by more than four orders of magnitude, reaching a value below that of the lower limit of our measurements, $R_{34} < 0.1\ \Omega$.

After exposing the film to laser light for 20 h, the laser was shut off. We then measured the temperature dependences of the resistances $R_{23}(T)$ and $R_{34}(T)$ of the irradiated films (Fig. 3). We found that, first, the dependences $R_{23}(T)$ and $R_{34}(T)$ which we measured are completely reproducible in the temperature interval 1.5–280 K; i.e., there is virtually no relaxation of the light-excited current carriers at these temperatures. Secondly, at temperatures below ≈ 40 K the temperature dependences of the resistance of an irradiated film exhibit a broad superconducting transition. The resistance of the low-resistance part of the film, $R_{34}(T)$, tends to zero ($R_{34} < 0.1\ \Omega$), while the resistance of the high-resistance part, $R_{23}(T)$, remains finite.

The effect we have observed basically has two explanations. We can assume that the annealed sample consists of superconducting grains which are separated by thin insulating layers. The effect of light on the sample will then involve only changing the thin insulating layers to the conducting state. We offer, however, a different explanation of the experimental results obtained by us. At low temperatures the superconducting regions of the test film begin to form and grow in size as a result of bombardment of the film with a laser light. The light-induced superconducting regions in the high-resistance part of the film in this case remain isolated. In the low-resistance part of the film (which is closer to the insulator-superconductor transition in terms of the oxygen concentration) the superconducting phase continues to increase to the percolation limit, where R_{34} vanishes. Evidence in support of the appearance of bulk superconductivity between contacts 3 and 4 is the fact that the I–V characteristic of the low-resistance part of the film is clearly nonlinear after the exposure to laser light (the inset in Fig. 3). We can thus assume that exposing a sample to laser light has the same effect as increasing its oxygen concentration x.

The transition to a state with frozen photoconductivity can be made at higher temperatures. We have therefore bombarded the film (200-mW laser) at a temperature near 100 K, where an increase in conductivity cannot be attributed to an increase in the superconducting phase. The resistances of the two parts of the film in this case decrease (because of the photoconductivity) by approximately 30% as a result of a 24-h exposure to laser light (Fig. 2). The magnitude of the photoconductivity and its time evolution in the two parts of the film, $R_{23}(T)$ and $R_{34}(T)$, are nearly the same at $T = 100$ K (in contrast with $T = 2$ K). This result suggests that the small fluctuations of the oxygen composition of the film at a temperature higher than that at which the superconductivity begins have only a slight effect on the transport properties. The temperature dependences $R_{23}(T)$ and $R_{34}(T)$ of the film bombarded by light at temperatures of 100 K and 2 K are qualitatively similar (Fig. 3). The bombardment of the film with laser light is more efficient at a temperature of 100 K than at 2 K.

As was mentioned above, the resistance of an irradiated film does not change with time at temperatures below 280 K. At room temperature we see a slow, nonexponential relaxation of the conductivity of the irradiated film to the equilibrium value which corresponds to a nonirradiated sample. At $T = 295$ K, the component of the conduc-

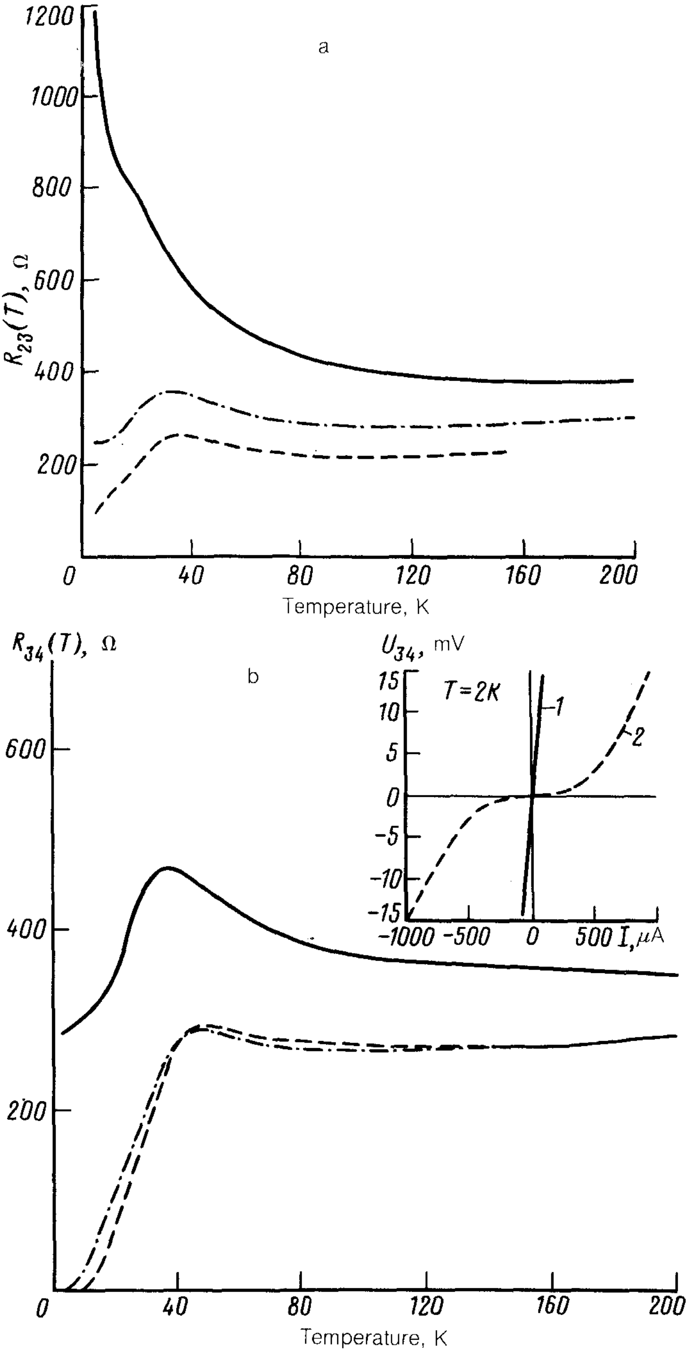

FIG. 3. Temperature dependence of the resistance of various parts of the annealed $YBa_2Cu_3O_{6+x}$ film (a) and $R_{34}(T)$ (b): the solid curves were obtained without exposure to the laser light; the dot-dashed curves—irradiation at $T = 2$ K for 19 h, laser power level 300 mW; dashed curves—irradiation $T = 100$ K for 24 h, 200 mW. The inset shows the I–V characteristic of the low-resistance part of the film, R_{34}, at $T = 2$ K before the exposure to laser light (curve *1*) and after the exposure (curve *2*).

tivity attributed to the frozen photoconductivity decreases by a factor of two in about 20 h. With an increase in temperature, the relaxation time decreases sharply; at $T = 320$ K the relaxation time amounts to several (~ 4) hours. The frozen photoconductivity disappears in several days and the transport properties of the film return completely to those it has before the exposure to a laser light. We observed the frozen conductivity effect in several samples.

We hope that the effect of frozen photoconductivity we observed in $YBa_2Cu_3O_{6+x}$ films would be useful in the study of the mechanism for the onset of superconductivity, and also in the study of the effect of free carriers on the magnetic order.

We wish to thank A. I. Usoskin and V. L. Sobolev for furnishing the $YBa_2Cu_3O_7$ films. We also thank A. S. Borovik-Romanov for interest in this study and useful discussions, and also I. P. Krylov for a discussion of the results.

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Translated by S. J. Amoretty