CHANGES IN THE SUPERCONDUCTING PROPERTIES OF HIGH-Tc CERAMICS PRODUCED BY APPLIED ELECTRIC FIELDS.

B.I.Smirnov, T.S.Orlova, H.-J.Kaufmann
A.F.Ioffe Physico-Technical Institute, Russian Academy of Sciences, St.Petersburg 194021, Russia

Abstract

Effect of an electrostatic field in the electrode-insulator-superconductor system on the current-voltage characteristics of high-Tc ceramics with various composition and different preparation technology has been studied at 77K. Ceramics of Y-Ba-Cu-O (123) and Bi-Pb-Sr-Ca-Cu-O (2223) systems and also ones doped by Ag have been used. Electric field strength has been up to 140 MV/m.
It has been shown that there are reversible changes in the critical current Ic and in the conductivity in electric field at the currents somewhat more than Ic at T<Tc, while at T>Tc the noticeable electric field effect has not been found. These effects are qualitatively similar in both ceramic systems. High negative and positive gate voltages result in an increase of the conductivity. The electric field effect is modified by magnetic field H. The field effect decreases with increasing magnetic field and disappears at H>30 Oe. In Y-Ba-Cu-O/Ag (10 wt.%) ceramics the field effect is practically absent.
It may be supposed that in the ceramics the field-induced effect is consistent with weak links at grain boundaries.

1. Introduction

Problem of an electric field effect on the conductivity of superconductors has attracted attention for more than 30 years [1-3]. The first experimental paper [1] reported that indium and tin films d≈70Å thick subjected to fields E=30 MV/m exhibited a change in the conductivity and a shift in critical temperature Tc by $\Delta Tc \approx 10^{-4}$K.

After the discovery of high-Tc superconductors similar studies were stimulated, especially during last four years [4-9]. In most cases thin films were objects of these investigations because it is usually believed that the field effect is attributed to a change of the carrier concentration in very thin surface layer of about 5Å thickness [6]. Considerable modulation of Tc and the current-voltage characteristics under applied electric field were reported [7-9].

At the same time there are data on the electric field effect in quite thick low-Tc superconductors. The 0.6K shift in Tc for $Ba(PbBi)O_3$ single crystals of 0.6 mm thickness was reported in [10]. In the case of high-Tc superconductors the field effect can occur also in less perfect samples of quite large thickness [11-14].

In the present paper we demonstrate the experimental evidence for considerable reversible effect of an applied electric field on the conductivity of high-Tc ceramics.

The following questions will be presented and discussed in the paper:

1. Reversible effect of an applied electric field on the current-voltage characteristics of high-Tc ceramics at T<Tc.
2. Influence of the electric field polarity on the effect.
3. The electric field effect in the presence of magnetic field.

4. Influence of silver addition to the ceramics on the effect.

2. Experimental

Main results have been obtained on yttrium ceramics of the 123 system. Some tests have been made on similar ceramics doped by silver and also on Bi-based compound of the 2223 system.

Samples of rectangular shape were prepared by standard powder sintering method and had dimensions of about 1.5x2x4 mm. By varying the anneal temperature and time, and the rate of the cooling, it was possible to obtain $YBa_2Cu_3O_{7-x}$ (YBCO) ceramics with various superconducting transition properties, the value of Tc remaining almost the same ($90K \le Tc \le 93K$) but the critical current density jc varying much more ($1A/cm^2 \le jc \le 120A/cm^2$) [15].

To obtain samples containing silver, the finished pure $YBa_2Cu_3O_{7-x}$ ($x \approx 0.07$) pellets were again crushed, and silver powder was added. Samples of this mixture were compacted and then twice annealed in oxygen at 930°C for 6 h, with crushing and compacting between the anneals. To verify the effect of silver on the ceramic properties, control samples were also prepared, and treated like the others except that no silver was added.

Investigations of field-induced effect were carried out in the metal-insulator-superconductor system shown in Fig.1. Teflon film of thickness l=50 μm was used as the insulator. Such a configuration allows us to apply considerable positive (or negative) gate voltage U up to 7 kV between the gate electrode and a superconductor.

Current-voltage (I-V) characteristics were taken with a standard four-probe technique, and Ic, the experimental critical current, was determined by a 1 μV/mm criterion.

It should be noted that the leakage current in the electrode-insulator-superconductor system did not exceed 3 nA at the maximum voltage U=7kV, whereas the transport current could reach a few amperes.

We studied effect of an electric field on the I-V characteristics of the ceramics. The experiment was carried out in the following way. At first I-V curve without electric field was measured. Then at some chosen point of this curve (Io-Vo) a gate voltage U was applied and drain-source voltage change ($\Delta V=V-Vo$) at a constant transport current was determined. Electric field ($E=U/l$) can be changed smoothly from 0 to 140 MV/m or some electric field Eo was switched sharply on or off. The similar measurements were made for various drain-source voltages Vo, i.e. for different transport currents. Also it was possible to measure and compare values of Ic and I-V characteristics without and with an electric field [16,17]. In addition, all the above mentioned experiments could be performed in a magnetic field H generated by an energized coil and directed parallel to the electric field [17].

3. Results and discussion

In the superconducting state, the I-V characteristics can be significantly affected by the gate voltage U (see Fig.2). Strong electric field shifts the I-V curve to the right, i.e. enhances the critical current and reduces the sample resistance R at I>Ic no matter what the polarity of the field.

Fig.3 shows change of drain-source voltage due to the switching of strong electric field on and off at 77 K. It is seen that voltage decreases at the moment when the field is switched on. The opposite effect is observed when the field is switched off. Strangely enough, we obtained qualitatively similar result also in the case when a metal foil 15 μm thick was placed between the insulator and a superconducting sample [18].

Thus, we can conclude that in the ceramic samples at temperature below Tc the field effect also exists. The value of drain-source voltage is restored after removing the field, i.e. the field effect has reversible character.

The following Fig.4 demonstrates characteristic experimental dependence drain-source voltage versus electric field for the cases of positive and negative gate voltages at 77K. As seen, the character of this relationship V(E) can depend on the field polarity. Applying a positive gate voltage to a fresh sample usually results in decrease of V ($\Delta V<0$). In the case of a negative gate voltage the value of V first rises with E ($\Delta V>0$) but then gradually decreases having a maximum at electric field $E \approx 40$ MV/m. After the electric field has reached $E \approx 60$-70 MV/m the value of ΔV changes its sign so that we have an decrease of the resistance. It is of interest that after the prolonged testing a sample the relationships V(E) can change essentially, including the appearance of maximum on the curve V(E) also for a positive gate voltage [19].

A qualitatively similar result was obtained for high Tc ceramic $Bi_{1.85}Pb_{0.35}Sr_{1.9}Ca_{2.1}Cu_{3.1}O_y$ ($Tc \approx 95K$) [16].

It should be also noted that in the above both cases the electric field effect exists only at T<Tc. At T>Tc the noticeable field effect was not observed [16].

Our further interest was in the elucidation of the electric field effect peculiarities arising from the application of a magnetic field. Fig.5 shows the influence of strong electric field E=-120 MV/m on the I-V characteristics of YBCO ceramic in various magnetic fields H. It is seen that the shift of the I-V curves under an electric field depends on the value of H. So, at H=0 the field effect is sufficiently large ($\Delta R/R = \Delta V/V$ can reach 100% for low V and about 40% for high V). However, it falls off with increasing H and practically disappears at $H \geq 30$ Oe.

Fig.6 presents the results on the influence of an electric and a magnetic fields on the critical current. At H=0, the critical current Ic is seen to grow with increasing E (see inset of Fig.6), the change reaching $\Delta Ic/Ic \approx 10\%$ at E=-120 MV/m. After the magnetic field is switched on, the electric field effect falls off rapidly, to practically disappear at $H \geq 30$ Oe. Thus, the electric field effect on the I-V curves is observed only at low magnetic fields.

Next we will consider the field effect in $YBa_2Cu_3O_{7-x}$ /Ag (10 wt.%) ceramics (YBCO/Ag). Fig.7 displays the comparison of the experimental results obtained for the pure YBCO and YBCO/Ag ceramic samples. As seen doping with silver suppresses the field effect practically completely.

Thus, the results obtained show that an applied electric field affects the current-voltage characteristics of high-Tc ceramics at T<Tc and can modify the value of the critical current Ic. The field effect is reversible. It should be stressed that the field effect observed in high-Tc ceramics is qualitatively different from the effect in the high-Tc films.

The question of what is the possible mechanism behind the observed field effect arises. Unfortunately, the nature of this effect has not been clear for us. It may be only supposed that in the ceramics the field-induced effect is consistent with change of weak link states at grain boundaries [16]. This is supported in particular by those facts that both magnetic field and doping with silver greatly suppress the electric field effect. In the latter case the marked reduction of the field effect can be explained replacing the weak links of superconductor-insulator-superconductor type (S/I/S) by the weak links of superconductor-normal metal-superconductor type (S/N/S) [20]. Further studies are required to gain a better understanding of the nature of the field effect observed.

4. Conclusions

In summary, the present study allows the following conclusions:

1. An applied electric field affects the I-V characteristics of high Tc ceramics at T<Tc and can modify the value of the critical current Ic.
2. In ceramic samples at T>Tc the noticeable field-induced effect was not found.
3. The effect has reversible character. Strong positive and negative gate voltages lead to enhancement of the conductivity.
4. Magnetic field and adding silver to the ceramics result in the suppression of the electric field effect.
5. It may be supposed that in ceramics the field-induced effect is consistent with weak links at grain boundaries.

References

1. Glover R.E. and Sherrill M.D. Phys. Rev. Lett. **5**, 248 (1960)
2. Sandomirskii V.B. Pis′ma Zh. Exp. Teor. Fiz. **2**, 396 (1965)
3. Meissner H. Phys. Rev. **154**, 422 (1967)
4. Mannhart J., Bednorz J.G., Müller K.A. and Schlom D.G. Z. Phys. B **83**, 307 (1991)
5. Mannhart J., Schlom D.G., Bednorz J.G., and Müller K.A. Phys. Rev. Lett. **67**, 2099 (1991)
6. Xi X.X., Doughty C, Walkenhorst A., Kwon C., Li Q. and Venkatesan T. Phys. Rev. Lett. **69**, 1240 (1992)
7. Mannhart J. Modern Phys. Lett. B **6**, 555 (1992)
8. Xi X.X. and Venkatesan T. Phys. News in 1992, Ed. Schewe P.F., American Inst. of Phys. 44 (1993)
9. Lemanov V.V. and Kholkin A.L. Fiz. Tverd. Tela **36**, 1537 (1994)
10. Bogatko V.V. and Venevzev Yu.N. Fiz. Tverd. Tela **29**, 2872 (1987)
11. Gomenyuk Yu.V., Lozovskii V.Z., Lysenko V.S., Pokhodnya K.N., Snitko O.V., Sytenko T.N. and Tyagul′skii I.P. Dokl. Akad. Nauk Ukr.SSR, ser. A, № 11, 49 (1989)
12. Gomenyuk Yu.V., Klyui N.I., Lozovskii V.Z., Lysenko V.S., Prokof′ev A.Yu., Romanyuk B.N., Sytenko T.N. and Tyagul′skii I.P. Sverkhprovodimost′: Fizika, Khimija, Tekhnika **4**, 762 (1991)
13. Smirnov B.I., Krishtopov S.V. and Orlova T.S. Fiz. Tverd. Tela **34**, 2482 (1992)
14. Lemanov V.V., Kholkin A.L. and Sherman A.B. Pis′ma Zh. Eksp. Teor. Fiz. **56**, 580 (1992)
15. Orlova T.S., Smirnov B.I., Shpeizman V.V., Stepanov Yu. P. and Chernova S.P. Fiz. Tverd. Tela **32**, 1031 (1990)
16. Smirnov B.I., Orlova T.S. and Krishtopov S.V. Fiz. Tverd. Tela **35**, 2250 (1993)
17. Smirnov B.I., Orlova T.S. and Kudymov A.N. Fiz. Tverd. Tela **36**, 1529 (1994)
18. Smirnov B.I., Orlova T.S. and Kaufmann H.-J. Fiz. Tverd. Tela **36**, 460, (1994)
19. Orlova T.S., Smirnov B.I. Supercond. Sci. Technol.(to be published)
20. Jung J., Isaac I. and Mohamed M.A-K. Phys. Rev. B **48**, 7526 (1993)

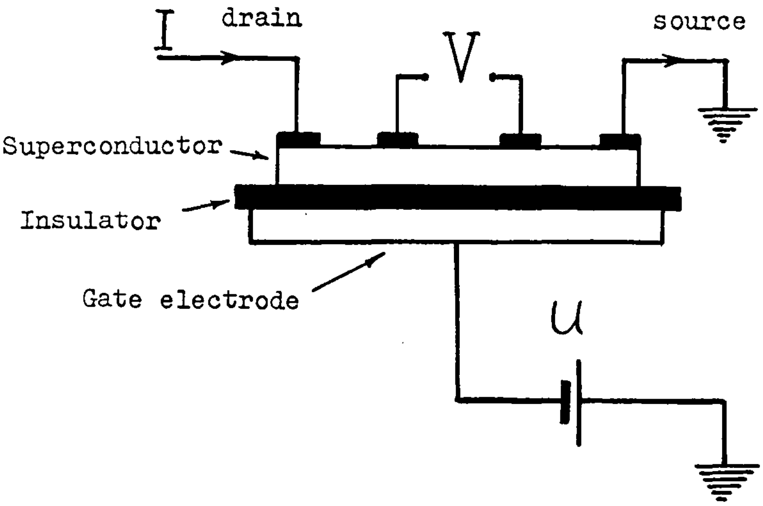

Figure 1.- Configuration used for the study of electric field effect.

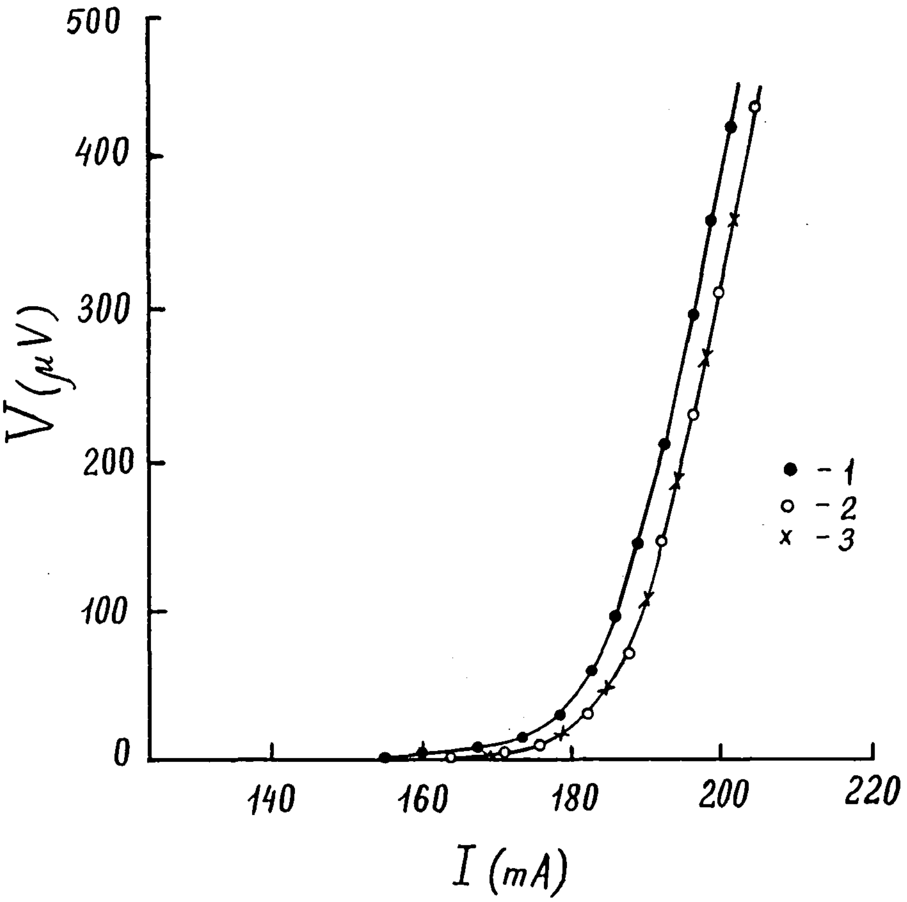

Figure 2.- Current-voltage characteristics of the YBCO ceramic with low jc≈5 A/cm^2 for electric field E(MV/m): 0 (1), -120 (2), and 120 (3). T=77K.

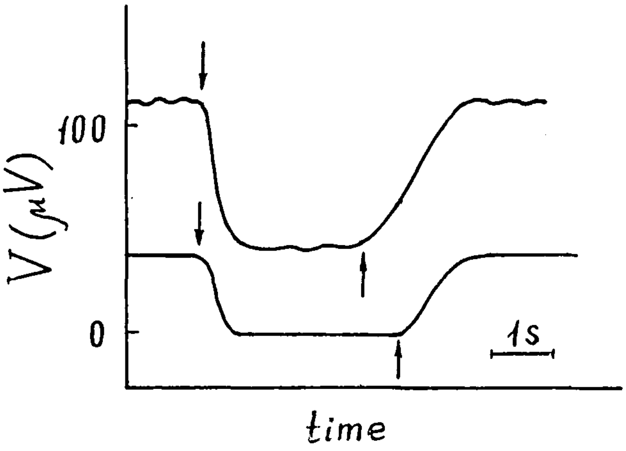

Figure 3.- Change in drain-source voltage V as a result of the switching of an electric field E=-120 MV/m on and off. T=77K. I=const in each experiment. The arrows show the times which the field was switched on (⇑) and off (⇓).

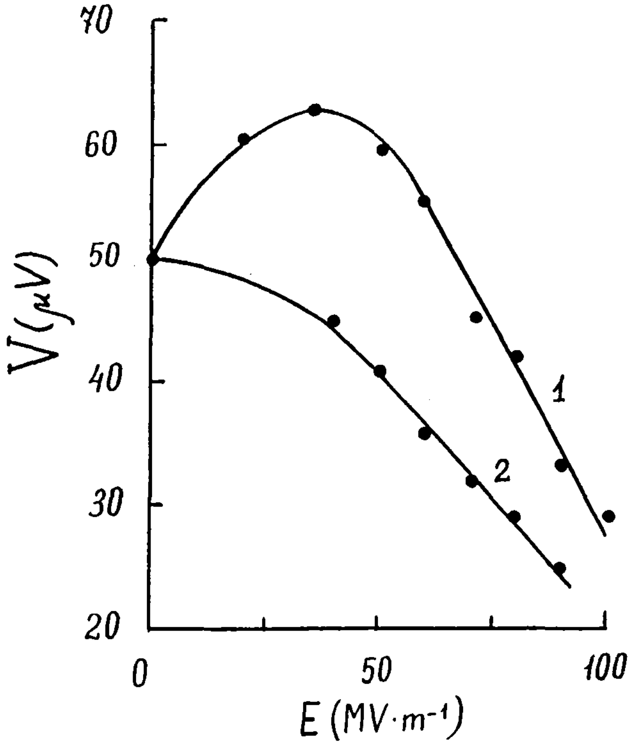

Figure 4.- Typical V (E) plots for the YBCO ceramic with negatively and positively biased gate electrode at 77K.

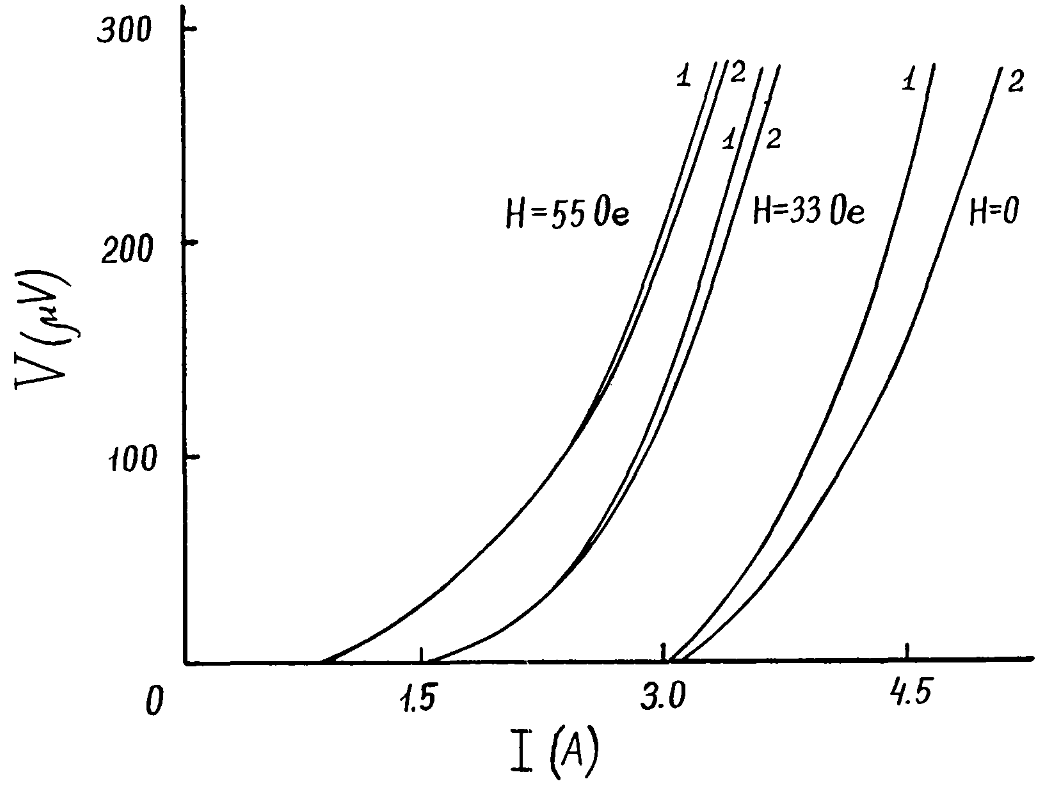

Figure 5.- Current-voltage characteristics of the YBCO ceramic with jc≈100 A/cm^2 on magnetic field H for the YBCO ceramic when E(MV/m): 0 (1), and -120 (2).

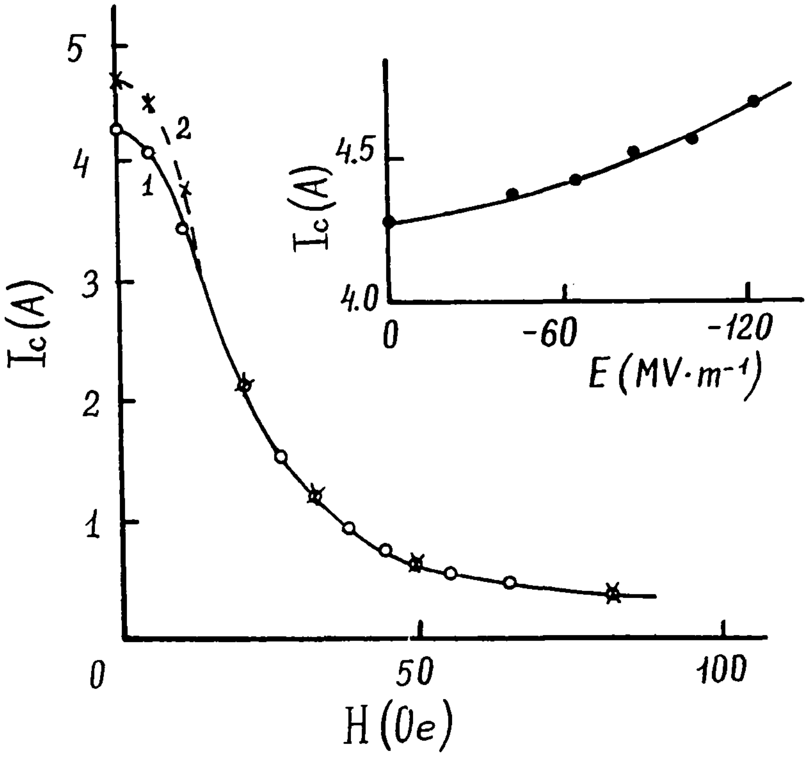

Figure 6.- Ic as a function of magnetic field H for the YBCO ceramic when E(MV/m): 0 (1), and -120 (2). Inset: Ic(E) dependence at H=0.

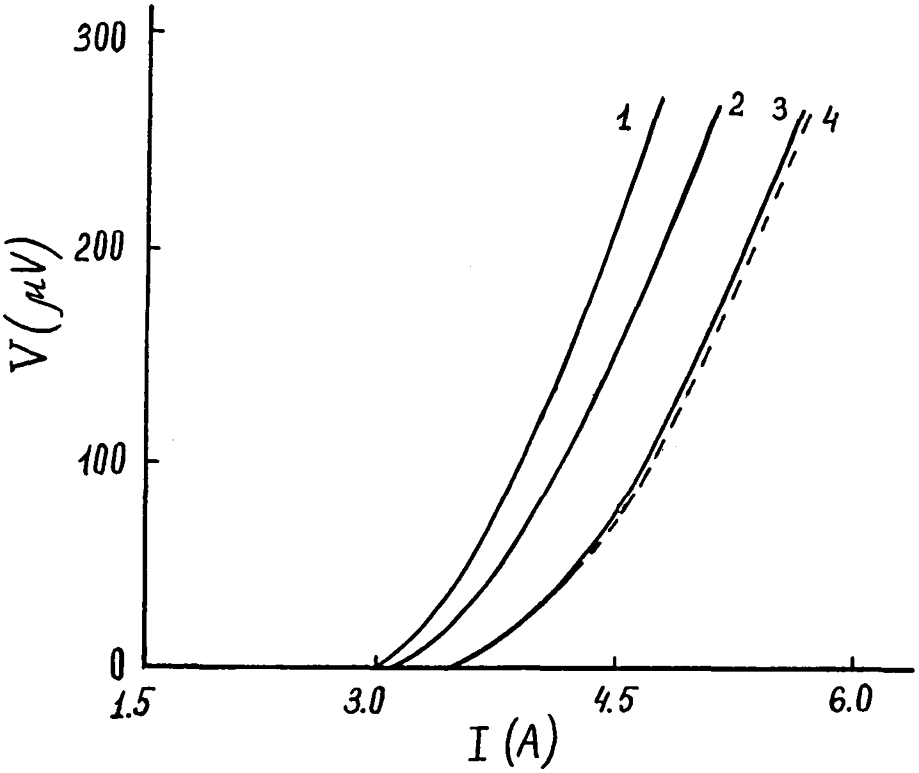

Figure 7.- Current-voltage characteristics of pure YBCO (1,2) and YBCO/Ag (10 wt.%) (3,4) ceramics for E(MV/m): 0 (1,3), and -120 (2,4).