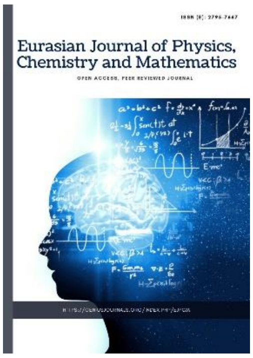

Magnetic Resistance And Mobility Of Carriers Of HTSC - YBCO Tapes Irradiated With 5 Mev Electrons

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ABSTRACT

Structural defects were studied in metal-coated microfilms of high-temperature superconductor $YBa_2Cu_3O_{7-x}$ on steel tape SuperOx-1, which were created by irradiation in air at 273 K with 5 MeV electron beam at a current of 400 nA to a fluency of $5x10^{14}$ e/cm^2. Magnetoresistance peaks within 100–300 K decreased by a factor of 10 after the irradiation, a correlated increase in resistivity by >10^3 times and a decrease in carrier mobility by >10^3 times were found at 120–160 K and 230 K. This indicates the formation of magnetic flux pinning centers, phase transitions of the 2nd order from a normal metal to a mixed magnetic vortex state, and then to the superconducting state. After the irradiation the fractions of Cu and Y_2O_3 crystal phases decreased due to generation of displacement defects of Cu and O atoms, and radiation-stimulated crystallization of the $YBa_2Cu_2O_7$ superconducting phase occurred simultaneously.

Keywords: High-temperature superconductivity, YBCO, electron irradiation, structural defects, magnetoresistance, charge carrier mobility

Introduction

Superconductivity is a phenomenon in which the electrical resistance of a material vanishes below a characteristic temperature, called the critical temperature, T_c. In 1911, H. Kamerlingh Onnes discovered superconductivity while investigating the electrical properties of metals under extremely cold temperatures. He found that Mercury's resistance suddenly dropped to zero below 4.2 K [1]. Later, more metallic elements such as Indium, Tin, and Lead showed superconductivity at 3.4 K, 3.7 K, and 7.2 K, respectively. Besides zero resistance, another interesting characteristic of a superconductor was discovered in 1933 by Meissner and Ochensenfield. They found that below T_c, the metallic superconductor completely expels the applied magnetic field from its interior and behaves like a perfect diamagnet [2]. Prospects changed dramatically in late 1986, when Bednorz and Muller discovered superconductivity at 30 K in the layered cuprate, $LaBa_2CuO_{4-x}$. In early 1987, superconductivity in $YBa_2Cu_3O_x$ (YBCO) at 92 K was announced, well above the boiling point of liquid nitrogen (77 K) [3]. The enhancement of critical current density J_c in films of high-temperature superconductor $YBa_2Cu_3O_x$ (YBCO) has attracted renewed interest, spurred by the development of second-generation 'coated conductor' films for power applications [4]. Second-generation tape high-temperature superconductors (HTSC-2) with copper coating are used to create high-current superconducting AC cables, in current leads of charged particle accelerators, inductive energy storage devices, windings of electric motors, etc. [5]. Studying the current-carrying capacity of such devices in dynamic modes (under the influence of electric and magnetic fields on HTSC) and determining the critical current J_c is an important practical task [6].

It is known from the scientific literature that, under certain conditions, exposure to ionizing radiation increases the critical current in $YBa_2Cu_3O_7$ superconductors in magnetic fields due to the generation of additional radiation defects that serve as pinning centers [7,8]. A numerical study was carried out using the Monte Carlo method to study the effect of strain on the critical current density and current-voltage characteristics of a high-temperature superconductor. It is shown that when the sample is deformed, the critical current density J_c and the slope of the E - J curve decrease [9,10]. Decrease in critical current density J_c was observed in a thin film of $YBa_2Cu_3O_{7-x}$ after its irradiation with electrons with an energy of 4 MeV with a dose of 3x10^{16} electrons/cm^2. The temperature dependence of J_c is consistent with the idea of a granular structure of a film with intercrystalline contacts of the superconductor-metal-insulator-superconductor type [11]. Later, the authors irradiated $YBa_2Cu_3O_{7-x}$ films with electrons with an energy of only 1 MeV. The maximum radiation dose of 4x10^{16} electrons/cm^2 was limited by the condition that defects formed as a result of electron-nuclear collisions cause a slight decrease in the critical temperature T_c. Under this condition, the main source of radiation effects may be the process of excitation of the electronic subsystem $YBa_2Cu_3O_{7-x}$ [12]. When YBCO films were irradiated with electrons from 20 keV to 2.4 MeV with doses from 10^{18} to 10^{22} electron/cm^2, a continuous decrease in T_c was observed with increasing dose. This agrees well with estimates of the number of defects formed at such doses by the mechanism of electron-nuclear collisions [13]. Previously, we achieved an increase in magnetization hysteresis (i.e., current J_m) in fields of 3–4 Tesla in YBCO single crystals after irradiation with electrons with energies of 300–350 keV (enough to displace only the oxygen atoms responsible for pinning at 0.5 Tesla) and 1 MeV (enough to displace copper atoms responsible for pinning at 3 Tesla) with doses up to 10^{19} cm^{-2} with decreasing T_c only by 2 K [14,15].

However, these encouraging results in the case of modern HTSC tapes with metal coatings should be sought under other irradiation conditions, taking into account the inevitable energy losses during the penetration of metal layers covering HTSC, the already discovered dose limits for reducing J_c and the need to preserve the HTSC phase c $T_c \sim 90$ K.

The purpose of this work was to determine the conditions of electron irradiation under which a spatial density of defects is achieved, ensuring an increase in the critical current in multilayer HTSC-YBCO tapes when a magnetic field is applied.

About objects and research methods

Objects. The objects of study were 2nd generation HTSC tapes, where a layer 5–8 μm thick of the superconducting composition $YBa_2Cu_3O_{7-x}$ was applied to a tape 40 μm thick and 4 mm wide made of S-276 steel (Ni-Cr-Fe) and coated with 3 microlayers of metals Ag, Cu, PbSn (industrial brand SuperOx, manufactured by S- Innovations, Russia-Japan, www.superox.ru) [16]. This tape design is intended for the production of compact electromagnetic coils, cooled with liquid nitrogen, generating a magnetic field above 2 Tesla. The laser evaporation method was used to form (001)$YBa_2Cu_3O_{7-\delta}$ epitaxial films on surfaces (1102) Al_2O_3 at T_c = 750 ^oC, which had critical values T_c= 88–90 K and J_c >10^6 A/cm^2 (77 K) [17].

Electron irradiation method.

Samples of tapes in the form of segments 5 cm long were attached parallel to the direction of beam scanning and irradiated at the Institute of Nuclear Physics of the Academy of Sciences of the Republic of Uzbekistan with an electron beam with an energy of 5 MeV at the Elektronika U-003 accelerator to a fluence of 5x10^{14} cm^{-2}, current 400 nA.

These values of electron energy, beam current and fluence were chosen taking into account the irradiation results presented in the review part of the article. It was estimated that such irradiation will create linear radiation defects at a distance of about 200 nm, corresponding to the depth of penetration of the magnetic field into a type 2 superconductor, around which a mixed vortex state in the form of a lattice will form, withstanding a magnetic field above 2 Tesla [7,18]. The critical temperature of the superconducting transition T_c of samples of HTSC composite tapes was determined from the dependence of resistance on temperature R(T) in the range 300–4.2 K. To measure current and voltage, resistive methods were used: four-probe measurements of current-voltage characteristics at direct current and pulse alternating current with a frequency of 50 Hz [19,20,21].

The magnetic characteristics were studied using the Hall effect measurement method using the Hall installation Effect Measurement System (HMS-7000). Samples for measuring resistivity ρand magnetoresistance *R* and carrier mobility were cut out in the form of tape sections 2–5 cm long and 4 mm wide. The sample was installed on a gold-plated table in the measuring cell and pressed with 4 spring contacts coated with gold (Fig.1).

After cooling to 80 K, a direct current *I* = 10 mA, a constant magnetic field *B* = 0.556 T was applied perpendicular to the plane of the tape and the voltage *V* was measured (potential difference) perpendicular to the tape and field in a slow heating mode from 80 to 320 K. To check the reproducibility of measurements and the contribution of low-temperature traps of charge carriers, the sample was again cooled to 77 K and re-measured in the same heating mode.

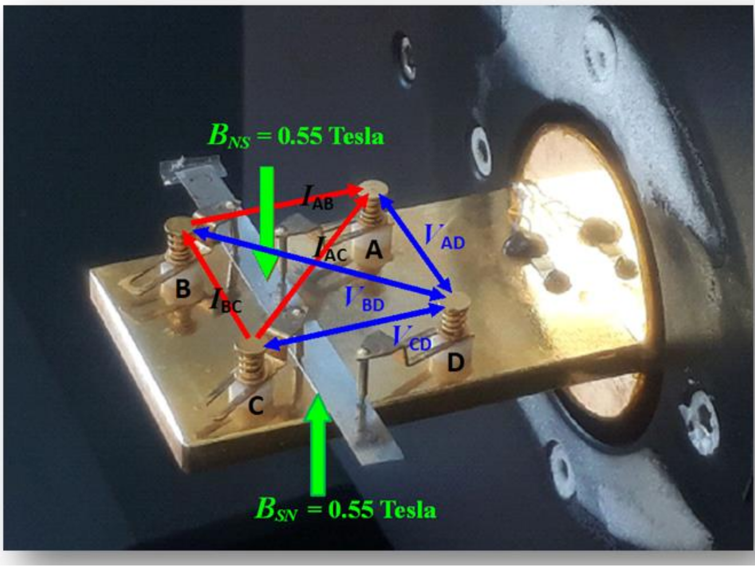
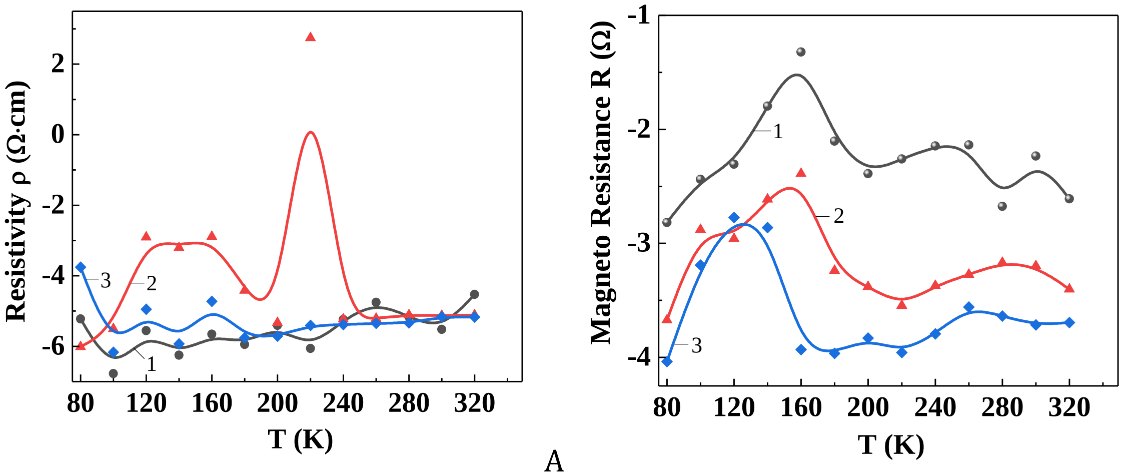


Fig.1. Measuring cell with 4 gold-plated contacts A-B-C-D, pressing the sample, arrows indicate the directions of the electric *V* and magnetic *B* field of 0.55 Tesla, as well as the current *I*

Results and discussion. Figures 2–3 show the temperature dependences of resistance ρ, magnetoresistance *R* and carrier mobility μ before and after irradiation.



A B

Fig. 2. Specific resistance in heating mode 80–320 K (A) and Magnetoresistance in the application of a field of 0.55 Tesla (B) of YBCO tape SuperOx-1:
1– before irradiation, 2– immediately after irradiation with electrons of 5 MeV at a current density of 400 nA/cm² up to an integral flux of 5x10¹⁴ cm⁻² in air at
273 K and 3– repeated measurement in heating mode

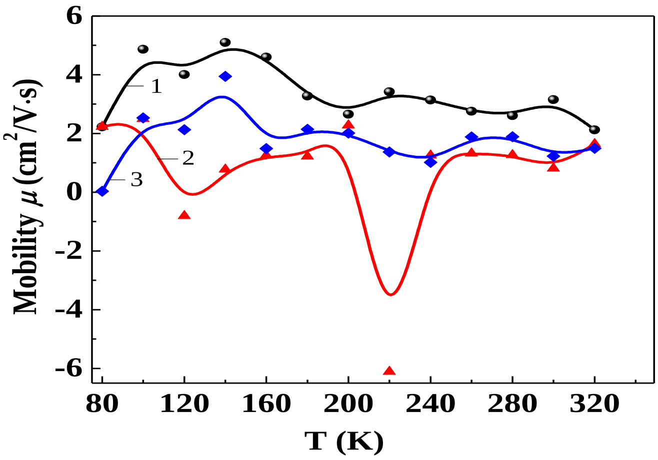


Fig. 3. Mobility of current carriers in heating mode 80–320 For SuperOx-1:
1– before irradiation, 2– immediately after irradiation with 5 MeV electrons at a current density of 400 nA/cm² up to an integral flux of 5x10¹⁴ cm⁻² in air at
273 K and 3– repeated measurement in heating mode

The main effect of electron irradiation is a significant (more than an order of magnitude) reduction in resistance, magnetoresistance, and a sharper superconducting transition below 100 K compared to an unirradiated standard. The carrier mobility after irradiation decreases by several orders of magnitude (Fig.3, curve 2), especially in the region of the onset of the superconducting transition, as well as at 120 and 220 K, when holes causing the paramagnetic signal are localized [22].

In Fig.4. X-ray diffraction spectra of YBCO tape SuperOx-1 are shown: before and after irradiation with electrons at the indicated doses, taken in reflection mode on an X-ray diffractometer Empyrean.

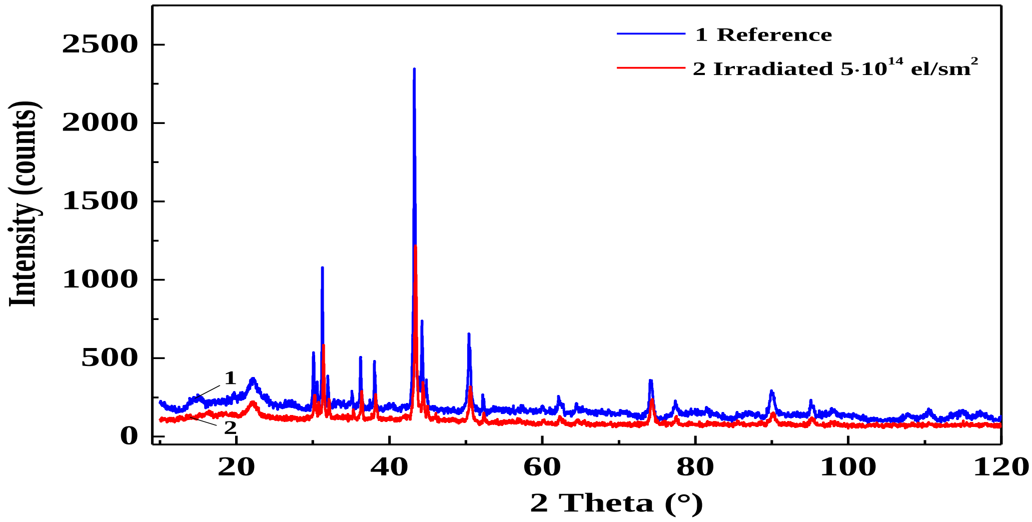
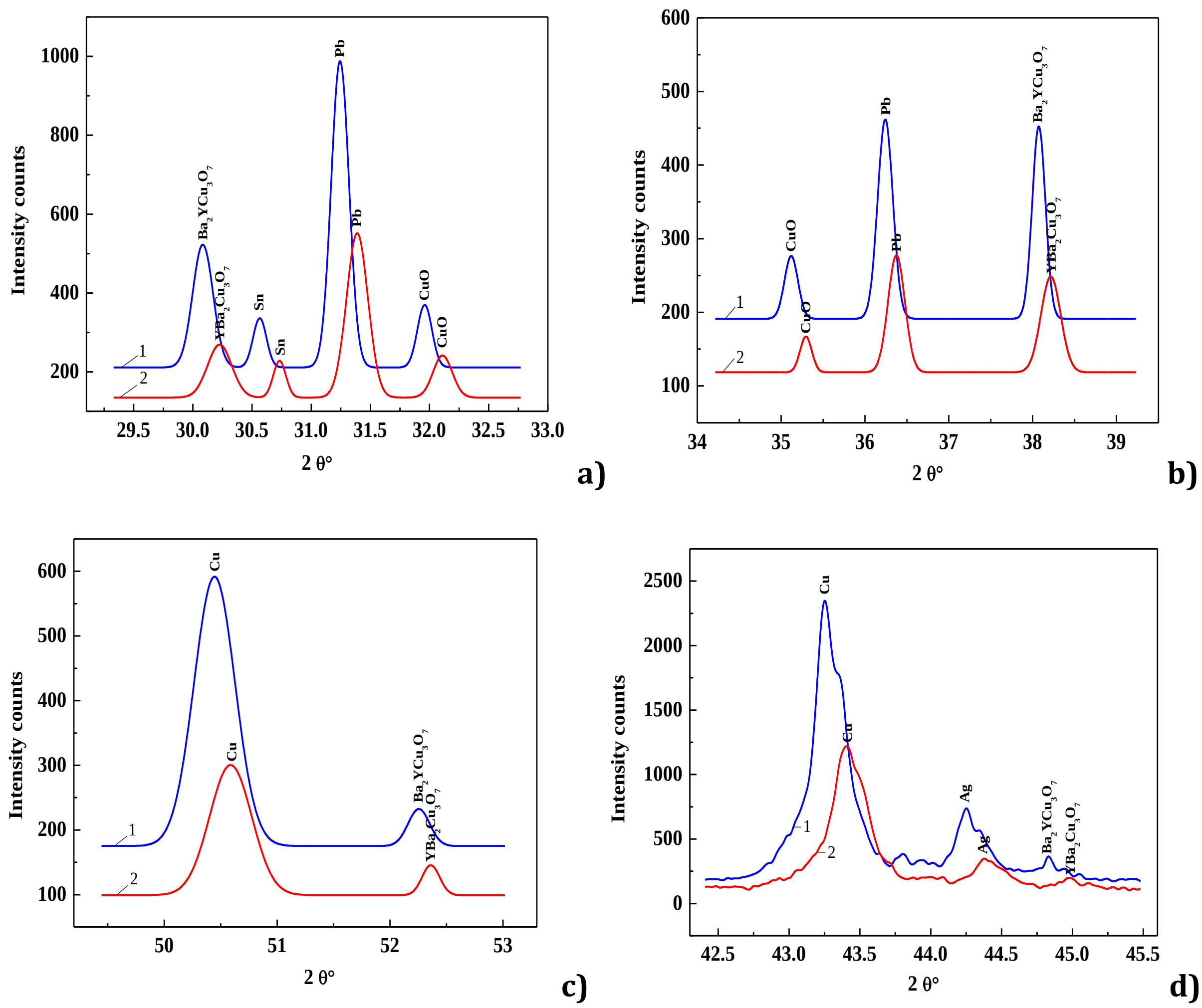


Fig.4. Survey spectrum of XRD HTSC tapes (SuperOx-1 -YBaCuO):
1 – before irradiation, 2 – immediately after irradiation with 5 MeV electrons at a current density of 400 nA/cm^2 integral flux 5x10^{14} cm^{-2}



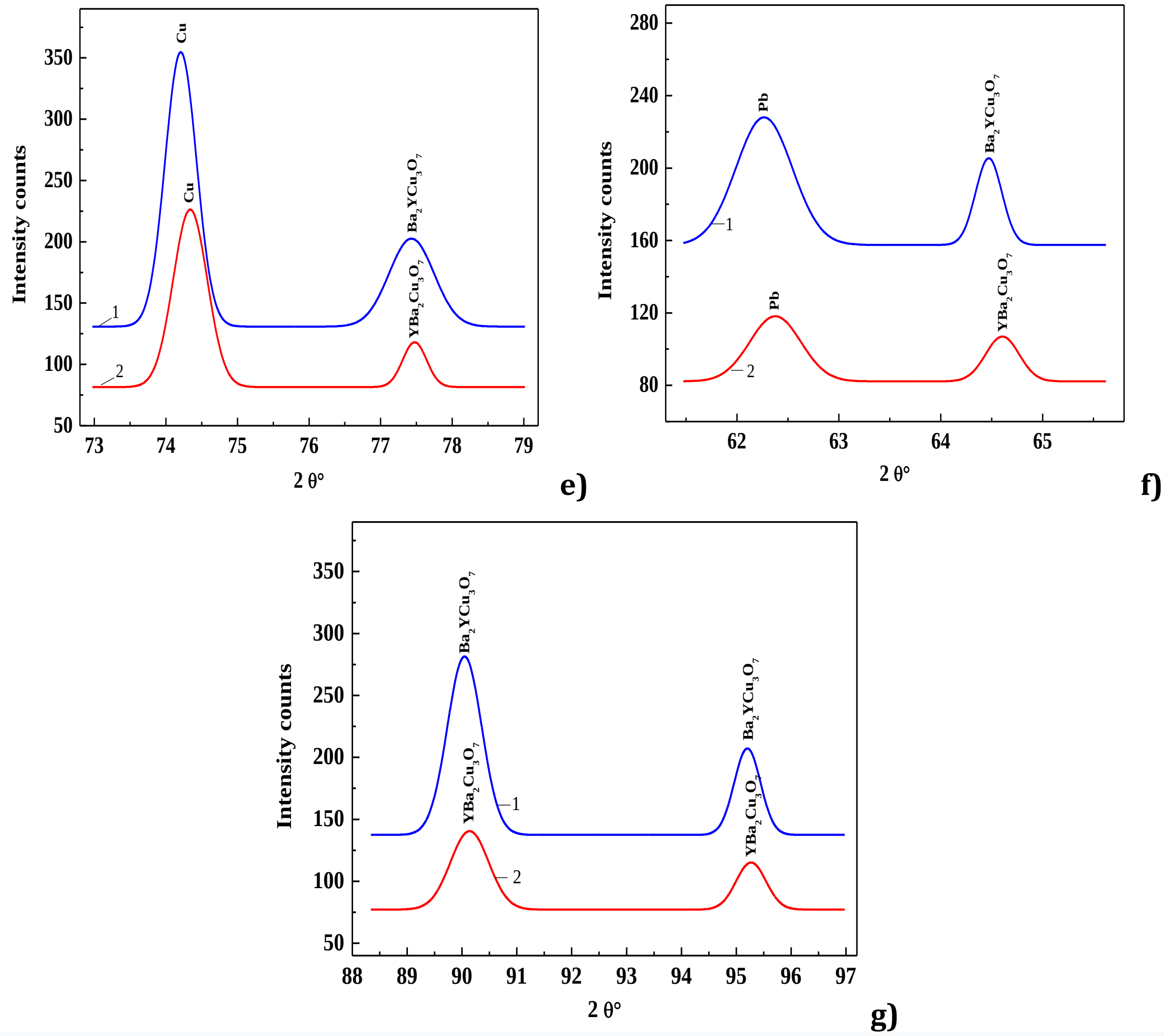


Fig.5. Fragments of the XRD spectrum of HTSC tapes (SuperOx-1 YBaCuO): 1– before irradiation, 2– immediately after irradiation with 5 MeV electrons at a current density of 400 nA/cm^2, integral flux 5x10^{14} cm^{-2}

The results of the structural-phase analysis of YBCO tape SuperOx-1 before and after irradiation are given in Tables 1 and 2.

Table 1
Shift of reflection maxima of YBCO-tape SuperOx-1

№	*I*, Reference (counts)	2 Theta (°)	Chem. Formula	*I*, Irradiated (counts)	2 Theta (°)	Chem. Formula
1	550	30.09166	Cu, Y_2O_3	271	30.27549	Cu, Y_2O_3
2	363	30.56435	Cu, Sn	226	30.74818	Cu, Sn
3	1093	31.22087	YBCO, Cu, Pb	595	31.37843	YBCO, Cu, Pb
4	404	31.95616	Cu, Sn	251	32.08747	Cu, Sn
5	302	35.10743	Cu, CuO	183	35.26499	Cu, CuO
6	526	36.23664	Cu, Pb	297	36.3942	Cu, Pb
7	495	38.04861	YBCO, Ag	275	38.17992	YBCO, Ag

8	2410	43.24821	Cu, CuO	1232	43.40577	Cu, CuO
9	762	44.24611	Cu,Ag,Y_2O_3	362	44.37741	Cu,Ag,Y_2O_3
10	668	50.39108	Cu	330	50.5749	Cu
11	275	52.20306	Pb	162	52.33436	Pb
12	244	52.33436	Cu	126	52.46566	Cu
13	367	74.10437	Cu	251	74.36698	Cu

Table 2
Phase composition determined in % from XRD spectra

Reference	$8Pb+6Sn+1Pb_{0.015}Sn_{0.985}+70Cu+1CuO+8Ag+3YBa_2Cu_2O_7+5Y_2O_3$
Irradiated	$8Pb+6Sn+6Pb_{0.015}Sn_{0.985}+54Cu+13CuO+7Ag+6YBa_2Cu_2O_7$

In the non-irradiated sample, weak reflections and an increased low-angle background from amorphous phases and intense reflections from crystalline phases were detected. Upper microlayer PbSn solder has practically decomposed into Pb crystallites and Sn, microtube Cu coated with a thin nanolayer CuO, and under it a crystalline microfilm of $YBa_2Cu_2O_7$, under which there is a thin crystalline layer of Y_2O_3 on the surface of the substrate steel tape.

As can be seen from the X-ray diffraction pattern (Fig.4, Fig.5) and Table 1, after irradiation with 2θ, the angles of the most intense reflections in the multilayer structure of the HTSC tape (where a surface layer of 3 μm PbSn is deposited on Cu) shift towards increasing angles, and their intensity decreases by half. After irradiation, the greatest decrease in intense reflections (~ 2 times) from Cu and Y_2O_3 also occurred crystallophases, because 5 MeV electrons are capable of creating displacement defects in copper and oxygen atoms and amorphizing the crystal lattice. Reflections increased accordingly due to radiation-stimulated crystallization of the superconducting phase of $YBa_2Cu_2O_7$ and $Pb_{0.015}$ $Sn_{0.985}$ solder (Table 2).

Conclusion.

Films of $YBa_2Cu_3O_{7-x}$ (YBCO)-tape SuperOx-1 were studied by X-ray diffraction methods. After irradiation with 5 MeV electrons, the proportions of Cu and Y_2O_3 decreased crystal phases due to the generation of displacement defects of Cu and O atoms, radiation-stimulated crystallization of the superconducting phase $YBa_2Cu_2O_7$ occurred simultaneously. It was found that the peaks of magnetoresistance in the range of 100–300 K after irradiation decrease by 10 times, a correlated increase in resistivity by >10^3 times and a decrease in carrier mobility by >10^3 times at 120–160 K and 230 K, this indicates the formation of centers magnetic flux pinning, about second-order phase transitions from a normal metal to a mixed magnetic state, and then to a superconducting state.

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