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Improving Structure and Superconductivity of Coated Cuprate Tapes by Irradiation with Electrons and Gamma-Rays

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Abstract: The analytic data were obtained with modern techniques: XRD, M(T,H), and Hall effect (0.556 Tesla). Below the radiation damage level of destroying the superconducting state, we found such structure modifications, when magnetic flux pinning centers are generated at the concentration of 10^{16}–10^{17} cm^{-3} and both T_c and J_c increase. Such an optimized current vortex state exists in 80–320 K. As irradiation with 1–5 MeV electron and 1.17–1.33 MeV gamma flux do not produce long living radio-nuclides, it is affordable for industrial technology of radiation treatment of long cable by rewinding across the flux.

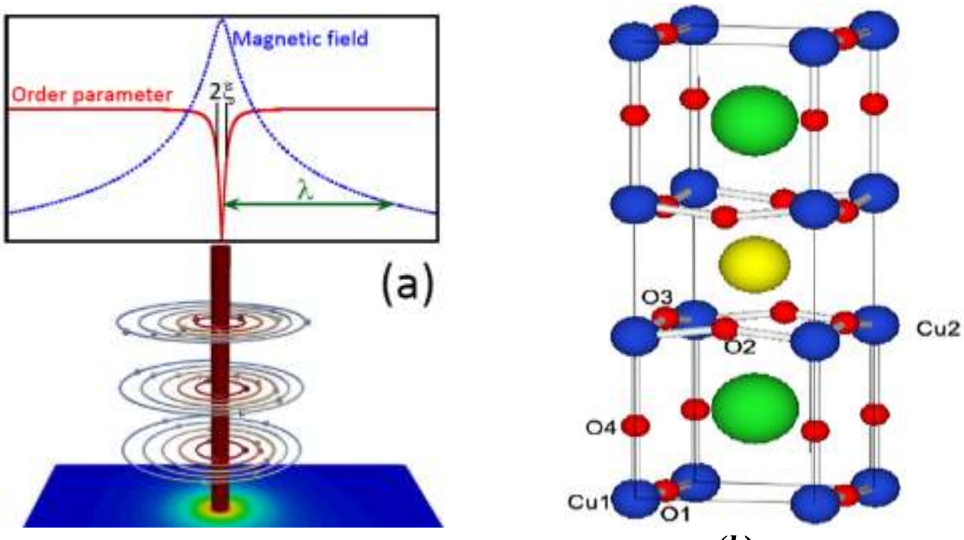
Keywords: high-T_c superconductors, electric power grid, radiation technology, pinning centers.

1. Introduction

High temperature superconductors (HTS) have been of great interest for practical applications since their discovery by Bednorz and Müller [1] with a T_c above 30 K. "Yttrium barium copper oxide" (YBCO) was the first HTS to exhibit superconductivity above the liquid nitrogen boiling point of 77 K and was discovered in 1987 by Wu [2]. It was soon followed by the discovery of superconductivity in similar materials. Its high critical temperature and its ability to withstand high magnetic fields make YBCO the superconductor of choice for future power applications such as energy transportation and generators, when fabricated in the form of wires.

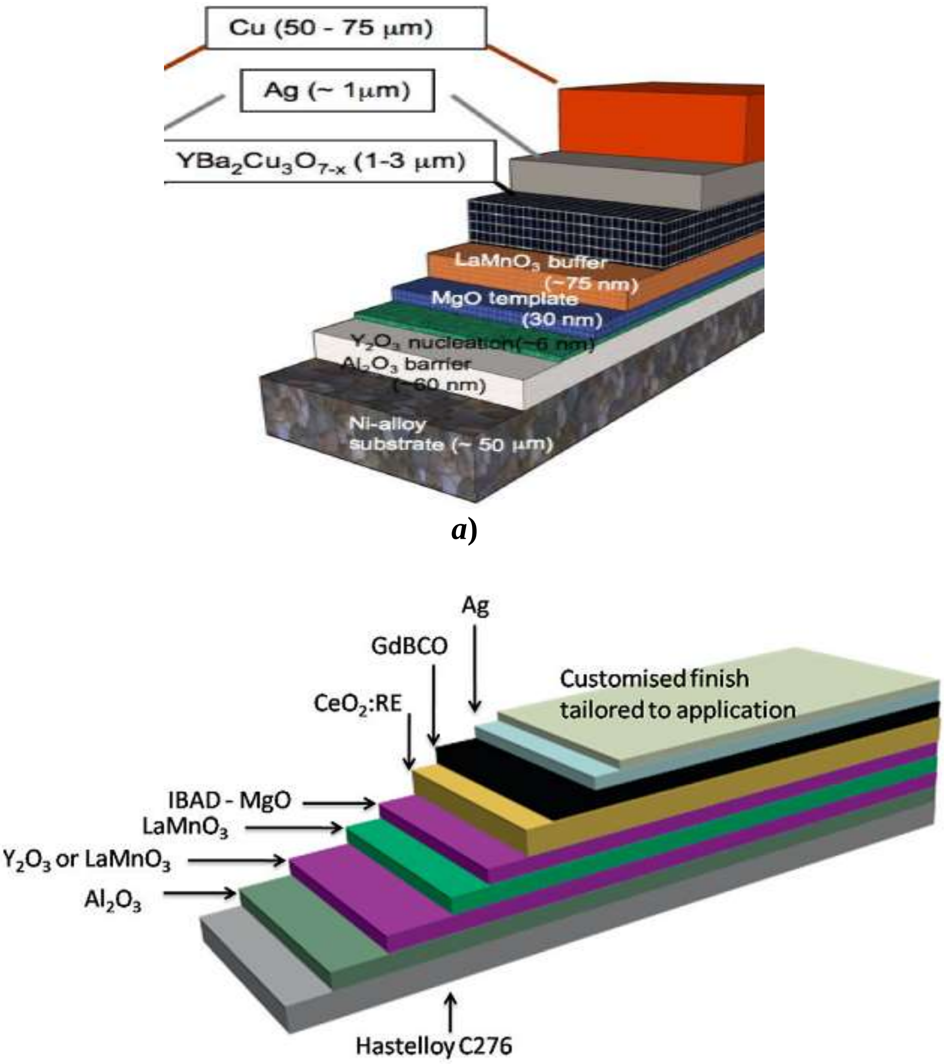
Superconducting single-domain YBCO and GdBCO/Ag bulks were tested for space and nuclear applications by an exposition to increasing doses of gamma and neutron radiation in the LVR-15 research reactor [3]. Maximum doses were 3.85E+04 Gy from neutron and 7.00E+05 Gy from gamma radiation, which is much larger dose then can be received in any spacecraft during the standard space mission [3]. Recently, a new method to increase the critical current of these coated tapes at high magnetic fields with ionic irradiation was shown. The proton implantation with an energy of 4 MeV and fluence of $8 \cdot 10^{16}$ protons/cm^2 twice increased the critical currents for H =6 kOe at T =27 K [4]. Further studies showed that oxygen ions with an energy irradiation of 3.5 MeV through a protective Ag layer of a 2G HTS superconducting tape could also reproduce the doubling of the critical current density in high magnetic fields [5]. The critical temperature (T_c) and the critical current density (J_c) decrease as an irradiation fluence increases. It was evidenced that the superconducting phase disappears for the fluence of $5 \cdot 10^{12}$ for $^{132}Xe^{27}$+ions/cm^2 and 10^{13} for $^{86}Kr^{17}$+ions/cm^2 [6]. For protons irradiation of 2.5 MeV, the radiation resistance of the $GdBa_2Cu_3O_{7-\delta}$ (GdBCO) 2G HTS tape is higher than that of the YBCO tapes. Compared to the YBCO tapes, the 2G HTS tape (GdBCO-based) exhibits better irradiation resistance due to the higher density of the GdBCO than the YBCO. The threshold for a decrease of the critical current densities is $6.2 \cdot 10^{15}$ protons/cm^2 for the GdBCO tapes and $2.7 \cdot 10^{15}$ protons/cm^2 for YBCO tapes [6]. In 1987 the first positive results of flux pinning at strong magnetic fields, causing the magnetization and J_c enhancement after moderate doses of neutron and ion irradiations in single crystal $YBa_2Cu_3O_{7-b}$ were published in [7]. Irradiation of YBCO single crystals with 2.5 MeV electrons in the superconducting state at 4 and 20 K to the dose 10^{18} cm^{-2} resulted in generation of positrons with a half-time 190 and 250 ps at 300 K, that is the direct evidence of nuclear reactions with Cu or O; even intensive laser pulse could induce oxygen disorder in CuO chains that recovered by heating > 200 K [8].

The unit cell of $YBa_2Cu_3O_7$ is shown in Fig.1. (***a***, *b*) Varying the oxygen content of $YBa_2Cu_3O_{7-x}$ results in significant changes of its physical properties. Many studies have shown that the critical temperature and crystal structure of $YBa_2Cu_3O_{7-x}$ change with oxygen content [9,10]. Neutron diffraction and magnetic measurements have shown that T_c is dependent on the charge balance between the copper-oxygen chains and copper-oxygen planes [11]. The chain sites serve as charge reservoirs from which electrons are transferred to the copper-oxygen planes as the oxygen content decreases. It is within the copper-oxygen planes that superconductivity originates. As the oxygen content of $YBa_2Cu_3O_{7-x}$ decreases, so does T_c.



(***b***)

Fig.1. (*a*) Structure of an isolated vortex (red). The top graph shows the distribution of the magnetic field and order parameter amplitude in a cross-section through the vortex. The vector-lines circling the vortex represent the supercurrent screening the magnetic flux of the vortex. The bottom plane-cut shows the distribution of the order parameter. (***b***) The unit cell of $YBa_2Cu_3O_{7-x}$ [12].



***b*)**

Fig. 2. Microstructure of layered coated tape *a*-$YBa_2Cu_3O_{7-x}$,

b- $GdBa_2Cu_3O_{7-\delta}$ [12]

The typical structure of the YBCO tape consists of the YBCO layer, the copper stabilizer layer, the silver stabilizer layer, the Hastelloy substrate and the buffer layer which is placed between the substrate and the YBCO layer [13]. The YBCO layer, which is the only layer responsible for conducting the load current during the steady state operation, is manufactured as a film with very small thickness, protected by copper stabilizer layers on both sides [14].

HTSC-2G tapes SuperOx-YBCO-1,2 and GdBCO-3 were manufactured by S-innovation by the patented method [15]. Cables made from GdBCO tapes pass the engineer current > 1.5 kA at 77 K, 3 kA at 65 K in self field, and 4 kA at 4.2 K in 8 T [16]. They contain 14-elements and have 7-layers with macroscale and micro-nanosized interfaces Ni-Cr-alloy/oxide-dielectric, HTSC/Ag, HTSC/dielectrics, Ni-alloy-Cu and Cu/Ag (fig.2). In this anisotropic structure of YBaCuO or GdBaCuO (fig.1 *b*) Y^{3+} is a scalar nonmagnetic impurity, and Gd^{3+} is a vector magnetic impurity, each separating two adjacent CuO_2 planes, where Cooper pairs move without energy dissipation [17]. Therefore their magnetic response differs one from another. Besides, the Ni- hastelloy substrate is ferromagnetic.

Here we report our latest researches on coated HTSC cuprate tapes aimed at improving crystal structure and enhancing the flux pinning at similar combined irradiation conditions.

Samples and experimental methods.
Industrial tapes YBCO and GdBaCuO (4 mm width, 60 μm thickness) on S-276 (Ni-Cr-Fe)-steel with a nanostructured insulating coating and covered with 3 microlayers of metals 3μAg, 4μCu, PbSn (trade-mark SuperOx, S-Innovations, Russia-Japan, www.superox.ru) [15,16,17,18,19]. Taking into account these results on the tapes and our early ones on YBCO crystals, we chose the following conditions: samples were irradiated in air with 5 MeV electron beam at current density 0.4–1 $\mu A/cm^2$ to doses 10^{14}–10^{15} el/cm^2 at 273–280 K, then irradiated in liquid nitrogen (77 K) by ^{60}Co γ-quanta of 1.17 and 1.33 MeV at dose rate 65 $R/s=5.85\times10^{11}$ $/cm^2s$ in converging field geometry to doses < 10^6 R, corresponding ~50 nm spacing of γ- quanta, which is > ξ_{ab} and < λ_{ab}, and according to [20], for inducing the largest flux pinning the point defect density is ~ 10^{12} cm^{-2}. Thus, these irradiation conditions would not destroy the Cooper pairs and leave some space for Abrikosov vortices around each point defect.
Crystal structure and phase composition were analyzed by X-ray diffraction spectrometer XRD Empyrean (PAnalytic, Netherland).
Magneto-resistance and current carrier mobility μ were measured by Hall method at magnetic field 0.556 Tesla || c-axis in the temperature range of 80–320 K at the system HMS-7000 (Ecopia, Korea).

Hall Effect Measurements.
Fig.3. *a*,*b*,*c* show the resistivity of the samples when I || B for non-irradiated and electron irradiated samples. Doses 10^{14} and $5\cdot10^{14}$ el/cm^2 were obtained at the beam current 0.4 μA, and 10^{15} cm^{-2} at 1 μA.

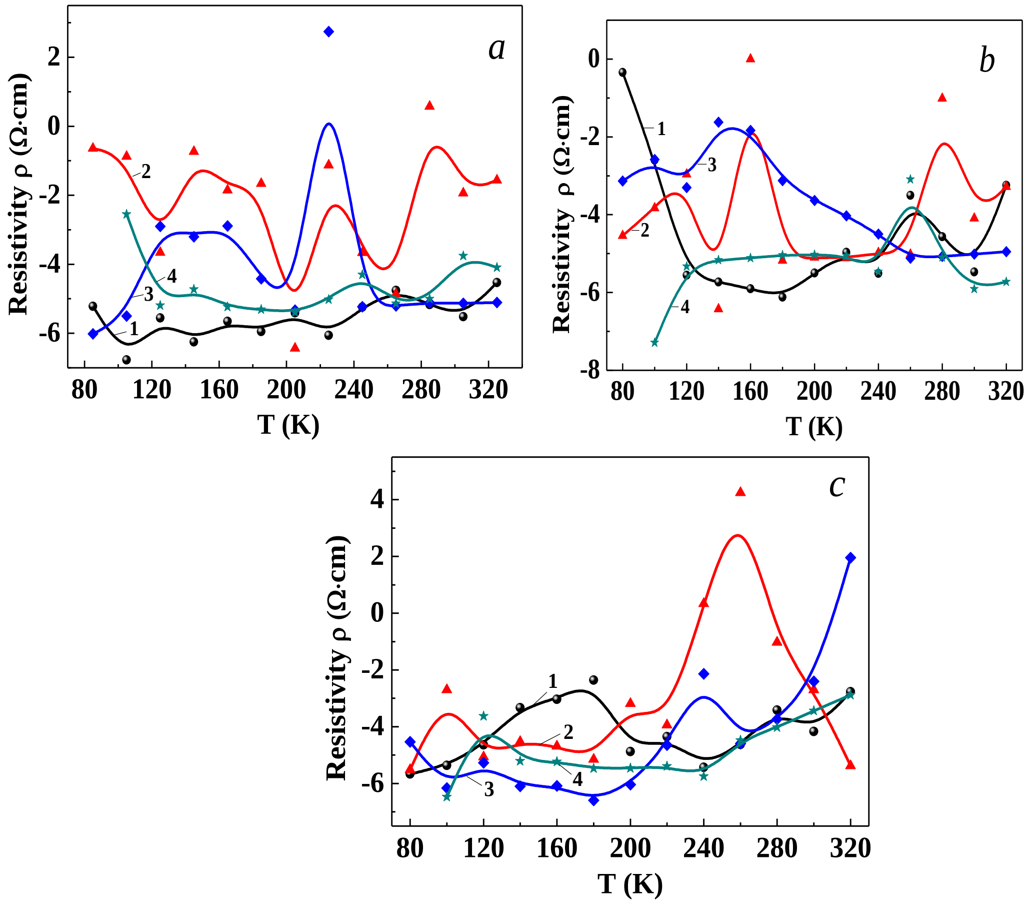


Fig. 3. Resistivity of the samples irradiated at 5 MeV electron beam in air: (*a*) -1-YBaCuO, (*b*) -2-YBaCuO, (*c*) -3-GdBaCuO: 1 – reference, 2 – 10^{14} el/cm^2;

3– $5 \cdot 10^{14}$el/cm^2, 4– 10^{15} el/cm^2

The electron dose 10^{15} cm^{-2} at the beam 1 μA/cm^2 (Fig.3 curves 4) have caused the shift of onset T_c to 120 K and significant drop of the resistivity at 100 K < 0.1 μΩ in 2-YBCO and < 1 μΩ in 3-GdBCO, which are less than in non-irradiated samples. Since the induced amorphization related to oxygen disordering (transition from superconducting orthorhombic to normal tetragonal phase), it recovered easily (resulting in the initial resistivity below μΩ·cm due to a higher oxygen mobility in CuO chains with plenty of oxygen vacancies and large defect instability area [8], when irradiated at the electron current density 1μA/cm^2 to the dose 10^{15} cm^{-2}.

Fig.4 *a*,*b*,*c* show the resistivity of the non-irradiated and γ-irradiated samples at 77 K.

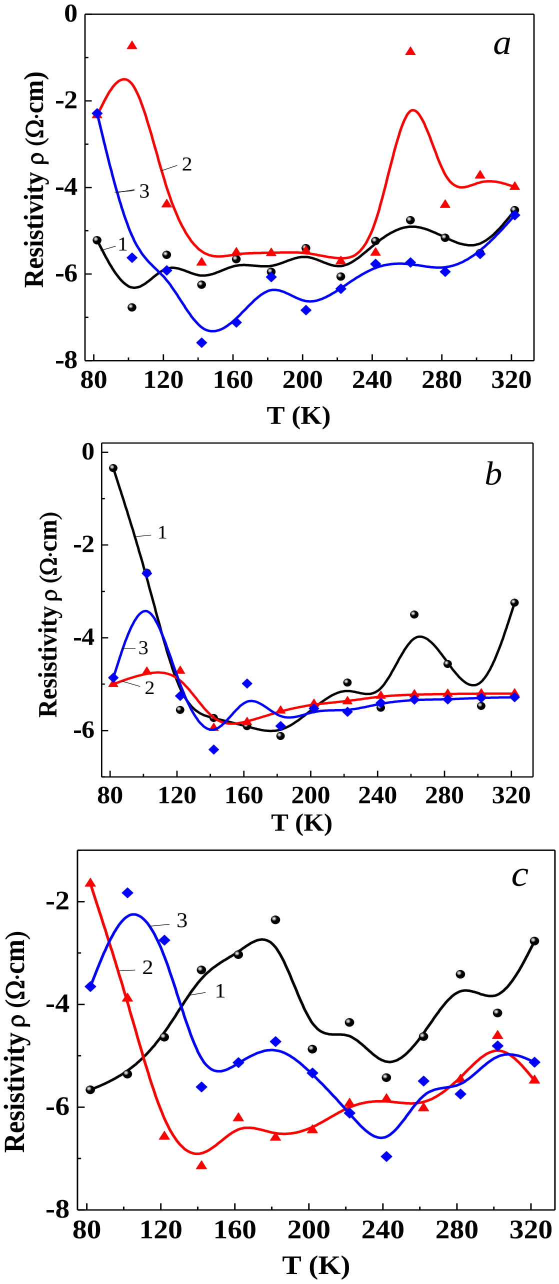


Fig.4. Resistivity of the samples irradiated with ^{60}Co γ- in liquid nitrogen: (*a*) -1-YBaCuO, (*b*) -2-YBaCuO, (*c*) -3-GdBaCuO: 1 – reference, 2 – $5 \cdot 10^5$ R; 3– additional dose $5 \cdot 10^5$ R (total 10^6 R)

Comparison of fig. 3 and 4 reveals the common resistivity peak at 100 K growing after the both kinds of irradiations and annealed < 200 K, which can be attributed to paramagnetic defects in Cu-O-chains. This result agrees well with our previous data on γ-irradiations at 77 K [15,21] and other's at 4–77 K caused by positron generation and reviewed in [8]. Unexpected difference in behavior just above T_c between 1-YBaCuO and 2-YBaCuO. Difference in peak at 260 K for both YBCO and at 280 K for GdBCO can be attributed to defects in double CuO_2 planes, which are spaced differently by non-magnetic Y^{3+} and magnetic Gd^{3+} [22]. Recent molecular dynamics simulations of radiation damage in $YBa_2Cu_3O_7$ demonstrated, that during the cascade of fast neutron induced defects, the interstitial sites between CuO chains (fig.1b) are populated with oxygen interstitials [23].

XRD structure and phase analyses.
At first one should emphasis, that XRD identifies the crystal structure and estimates its volume amount in % only for crystalline phases, while amorphous phases are seen as a broad scattering band at low angles. Non-irradiated samples 1-YBaCuO and 2-YBaCuO contain Y_2O_3 and CuO and 3-GdBaCuO contains Gd_2O_3 interface nanophases. It means, that the pinning centers in the non-irradiated tapes are oxide nanophases at the interfaces of HTSC. After electron irradiation to 10^{15} cm^{-2} there appeared 22% of a new $YCuO_2$ nanophase in 1-YBaCuO; the superconducting $YBa_2Cu_3O_7$ phase increased up 47% at the expense of Y_2O_3 and CuO phases decrease, the ration of Gd_2O_3 to $GdBa_2Cu_3O_7$ increased, i.e. the irradiation induced recrystallization of the interfaces.

Conclusions and Perspectives.
As irradiation with 5 MeV electrons and 1.17–1.33 MeV gamma flux do not produce long living radio-nuclides, it is affordable for industrial technology of radiation treatment of long cable by rewinding across the flux. Thus effect of nuclear irradiation does not always damages structure and degrades functions of materials. There exist particular ranges of energy/intensity/dose/temperature where structure modification may result in improving the properties and even find new functions for old materials.

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