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MAGNETIC RESISTANCE OF YBaCuO, GdBaCuO HTSC TAPES IRRADIATED WITH 1–5 MeV ELECTRONS AND ^{60}Co GAMMA RAYS

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Abstract. The article presents Hall effect (80–320 K at magnetic field 0.556 Tesla) data in YBCO, GdBCO microfilm on 276-steel tape with metal coating exposed. The tape samples were irradiated with an electron beam with an energy of 5 MeV at currents of 400 nA and 1 μA with fluences of 10^{14}, $5{\cdot}10^{14}$ and 10^{15} el/cm^2 in air at 273 K and ^{60}Co gamma-quanta of 1.17–1.33 MeV in the dose range 10^5–10^6 R at liquid nitrogen (77 K). This irradiation resulted in structure modification of microinterfaces YBCO-AgCu, ten times decrease in the magnetoresistance > T_c, increase in the 2-nd type phase transition steep. 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.

Key words: HTSC tape, YBCO, GdBCO, electron irradiation, ^{60}Co gamma-irradiation, defect ordering, superconducting transition of the second type, magnetoresistance, radiation technologies, pinning centers.

МАГНИТНОЕ СОПРОТИВЛЕНИЕ ВТСП ЛЕНТ YBaCuO, GdBaCuO, ОБЛУЧЕННЫХ ЭЛЕКТРОНАМИ С ЭНЕРГИЕЙ 1–5 МэВ И ГАММА-ЛУЧАМИ ^{60}Co

А.А. Шодиев, М.А. Муссаева, Д.Б. Элмуротова

Аннотация. В статье представлены данные по эффекту Холла (80–320 К в магнитном поле 0,556 Тесла) в микропленке YBCO, GdBCO на ленте из стали 276 с обнаженным металлическим покрытием. Образцы лент были облучены пучком электронов с энергией 5 МэВ при токах 400 нА и 1 μA флюенсами 10^{14},

$5{\cdot}10^{14}$ и 10^{15} эл/см^2 на воздухе при 273 К и ^{60}Co-гамма-квантами 1,17–1,33 МэВ в интервале доз 10^5–10^6 Р при жидком азоте (77 К). Такое облучение привело к модификации структуры микроинтерфейсов YBCO-AgCu, уменьшению магнитосопротивления в десять раз > T_c, увеличению крутизны фазового перехода 2-го типа. Ниже уровня радиационного повреждения, приводящего к разрушению сверхпроводящего состояния, мы обнаружили такие модификации структуры, когда центры закрепления магнитного потока генерируются с концентрацией 10^{16}–10^{17} см$^{-3}$ и увеличиваются как T_c, так и J_c. Такое оптимизированное токовое вихревое состояние существует в диапазоне 80–320 К. Поскольку облучение электронами с энергией 1–5 МэВ и гамма-потоком 1,17–1,33 МэВ не приводит к образованию долгоживущих радионуклидов, оно доступно для промышленной технологии радиационной обработки длинных кабелей перемотка поперек потока.

Ключевые слова: ВТСП-лента, YBCO, GdBCO облучения электронами, ^{60}Co гамма-облучение, дефекты структуры, сверхпроводящий переход 2 рода, магнитосопротивление, радиационные технологии, центры пиннинга.

1–5 MEV ENERGIYALI ELEKTRONLAR VA ^{60}Co GAMMA NURLARI BILAN NURLANTIRILGAN YHO‘O‘ YBaCuO, GdBaCuO TASMALARINING MAGNIT QARSHILIGI

A.A. Shodiyev, M.A. Mussayeva, D.B. Elmurotova

Annotatsiya. Maqolada tasma shaklidagi metal qoplamali 276 po'lat taglikka o’tqazilgan YBCO, GdBCO mikroplyonkalarining Hall effektida (magnit maydoni 0,556 Tesla, harorat 80–320 K oralig’ida) o’lchangan ma'lumotlari keltirilgan. Tasmalar namunalari 400 nA va 1 μA toklarda flyuenslari: 10^{14}, $5{\cdot}10^{14}$ va 10^{15} el/sm^2 va energiyasi 5 MeV bo’lgan elektronlar bilan 273 K havoda hamda 1,17–1,33 MeV energiyali ^{60}Co gamma-nurlarida suyuq azot (77 K) da 10^5-10^6 R dozalar oralig'ida nurlangan. Bunday nurlanish YBCO-AgCu mikrointerfeyslari strukturasining o‘zgarishiga, magnit qarshilik >T_c ning o‘n baravar kamayishiga va 2-turdagi fazaviy o‘tishning keskinligi oshishiga olib keldi. Biz o’tao'tkazgich holatning buzilishiga olib keladigan radiatsion shikastlanish darajasidan pastroqda, 10^{16}–10^{17} sm^{-3} konsentratsiyali magnit oqimining pinning markazlari hosil bo'lganda hamda T_c va J_c larning ortib borishidagi strukturaviy modifikatsiyalarni aniqladik. Bunday optimallashtirilgan tok girdob holati 80–320 K oralig'ida mavjud. Energiyasi 1–5 MeV bo’lgan elektronlar va 1,17–1,33 MeV energiyali gamma nurlari bilan nurlanish ta’sirida uzoq muddatli radionuklidlarning hosil bo'lmaganligi sababli undan sanoatda, uzun kabellarni nurlanish oqimi bo’ylab teskari o'rash texnologiyasi vositasida radiatsion ishlov berish orqali foydalanish mumkin.

Kalit so'zlar: YHO’O’ tasmasi, YBCO, GdBCO elektron nurlanishi, ^{60}Co gamma nurlanishi, strukturaviy nuqsonlar, ikkinchi tur fazaviy o’tish, o'tao'tkazuvchanlik, magnitqarshilik, radiatsion texnologiyalar, pinning markazlari.

Introduction

In 1987, the first superconducting compound with a critical temperature above the boiling point of nitrogen was discovered - $YBa_2Cu_3O_{7-x}$ [1]. Then it took about another 20 years to develop sophisticated technologies that ensured the production of composite tape-wires, which in their reliability could be compared with metal current conductors, for example, made of copper. The culmination of the efforts of scientists and engineers around the world was the creation of flexible long-length multilayer HTSC wires of the second generation (HTSC-2), which have a critical current density above 1 MA/cm^2 at 77 K in their own magnetic field [2]. In the 21st century, 2-nd generation HTSC wires and tapes are produced based on $YBa_2Cu_3O_{7-x}$ for 200 A power cables and 500 MVA (77 K) current limiters for electrical networks, current generators (65K) for wind power plants, $GdBa_2Cu_3O_{7-x}$ for magnetic coils for 10–20 Tesla ⊥ c-axis (10–20 K) in accelerator and medical technology [3–5]. To achieve such high performance, technologists are developing both chemical and radiation methods for creating nano-sized pinning centers - magnetic flux capture. HTSC wires of the 1st and 2nd generations are currently commercially available are produced in lengths up to a kilometer by many companies such as SuperPower, American Superconductor, Fujikura, SuNAM, SuperOX, based on them, prototypes of electrical devices 5 of the future are created. The area of application of HTSC wires is quite extensive and in the near future will occupy almost the entire niche of special electrical engineering. In particular, we should expect their applications in medicine (proton beam therapy, magnetic resonance imaging), in the field of production and use of electricity (current limiters, induction storage devices, generators, electric motors), in the field of scientific research: magnets capable of creating strong fields with an induction of more than 25 Tesla, in high energy physics (ITER project - international experimental thermonuclear reactor), for transport purposes (magnetic trains - MAGLEV project), in military equipment (powerful small-sized on-board generators, ship demagnetization devices, railguns) [6]. In progress [7] Second-generation HTSC ribbons were irradiated with high-energy electrons of 23 MeV, as well as heavy ions $^{132}Xe^{27+}$ (167 MeV), $^{84}Kr^{17+}$ (107 MeV), $^{40}Ar^{8+}$ (48 MeV) with different fluences. Samples (SuperPower SCS 4050) irradiated with electrons with an energy of 23 MeV in the fluence range $F=1.0\times10^{17}$–3.0×10^{18} electron/cm^2 showed no change in critical parameters. In progress [8] it has been shown that electron irradiation leads to the appearance of macroscopic composition fluctuations in the sample (comparable to the thickness of the sample), which coexist with mesoscopic fluctuations. A decrease in Tg was also detected due to changes in oxygen deficiency and/or the appearance of displaced Cu, Y and Ba atoms.

In the normal state, a minimum resistance is observed at T≈104 K, which after irradiation shifts towards high temperatures. In progress [9], electrons with an energy of 1 MeV cause displacements in Y-Ba-Cu-O of any of the four types of atoms - O, Cu, Y and Ba. In progress [10] it has been shown that defects in the form of non-magnetic atoms lead to a decrease in T_c. Therefore, in work [8] the decrease in T_c may be caused both by an increase in oxygen deficiency and by Cu, Y and Ba atoms, incident electrons displaced from their regular positions. Thus, electron irradiation led to the emergence of macroscopic fluctuations in the concentration of defects along with the already existing mesoscopic fluctuations, and also to a decrease in T_c both due to an increase in oxygen deficiency and due to Cu, Y and Ba atoms displaced from their regular positions.

Figure 1 and Table 1 show the crystal structure of yttrium-barium-copper oxide and the physical and thermal properties of yttrium-barium-copper oxide (YBCO).

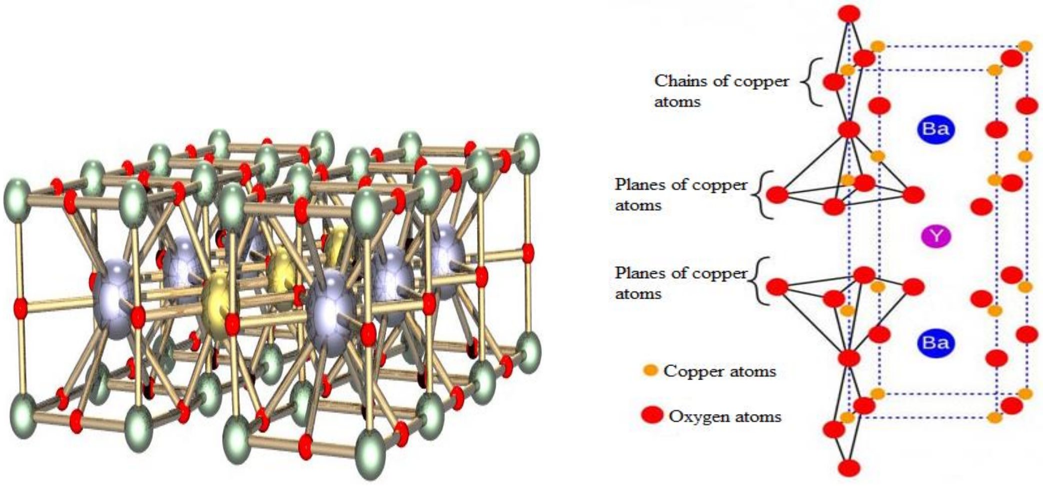

Fig.1. Crystal structure of yttrium-barium-copper oxide [11]

Table 1

Physical characteristics Yttrium - barium - copper oxide (YBCO) [1]

Yttrium Barium Copper Oxide (YBCO)	
Systematic name	Yttrium-barium-copper oxide
Chemical formula	$YBa_2Cu_3O_{7-x}$
State	Solid
Molar mass	666.19 g/mol
Density	6.3 г/см^3 [1,11]
Melting temperature	> 1000 °C

Second-generation HTSC wires are a complex layered architecture, including a metal substrate tape, buffer layers, a HTSC layer, a protective silver layer, a shunt layer and an insulation layer (Fig. 2).

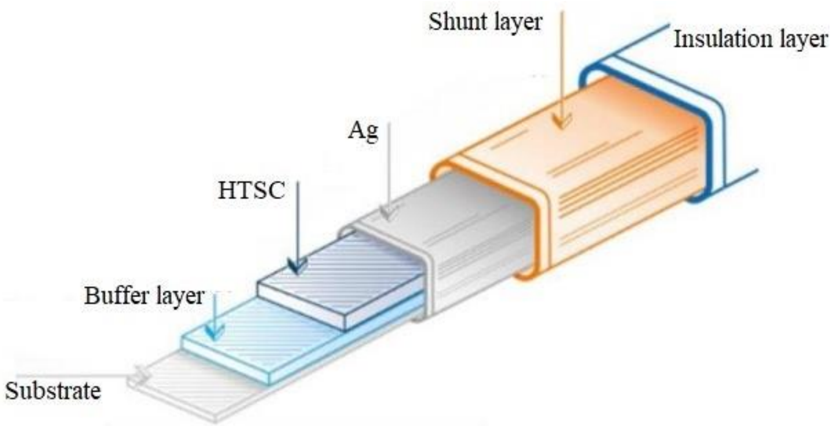

Fig.2. Structure of second generation HTSC tapes [12]

In the work [13] the results of resistive and magnetic measurements of the current-carrying capacity of HTSC-2 tapes based on $GdBa_2Cu_3O_{7-x}$ (GdBCO) are presented, manufactured by the SuperOx company using the pulsed laser deposition method. The results obtained are compared with the characteristics of $YBa_2Cu_3O_{7-x}$ (YBCO) tape produced by chemical deposition (SuperPower, USA).

In Fig.3 shows the layered structure of GdBCO (SuperOx) (a) and YBCO (SuperPower) (b) tapes.

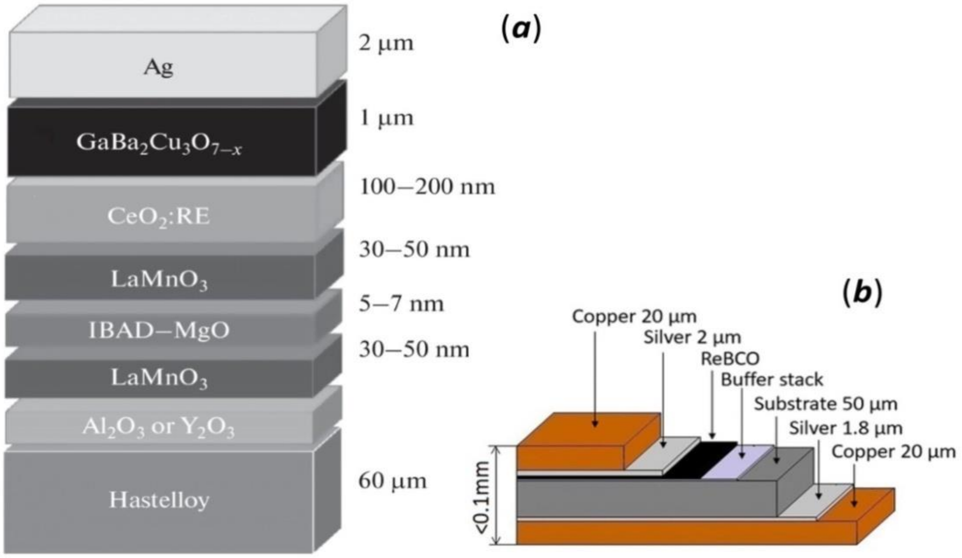

Fig.3. Structure of GdBCO (SuperOx) tapes (a) and YBCO (SuperPower) (b) [13]

SuperOx company develops cost-effective technologies for the production of $GdBa_2Cu_3O_{7-x}$ tapes using the most advanced methods of chemical and physical layer deposition [13]. Tapes with a width of 12.6 or 4 mm have a multilayer structure, containing a metal substrate (Hastelloy C 276), several buffer layers of metal oxides and a $GdBa_2Cu_3O_{7-x}$ superconductor film with a thickness of 1–3 µm, coated on top with a layer of Ag 1–2 µm thick (see Figure 3 a)).

The aim was to find optimal irradiation conditions at some energy/flux/fluency for generating particular PC in YBaCuO or GdBaCuO deposited on Ni-steel tape and coated by Ag, Cu and PbSn micro-films (SuperOx, S-Innovations, Russia), when the distance between the neighboring PC fits two current vortices, and understand the pinning mechanisms.

Research methods and the Received Results

Objects. The objects of study were 2nd generation HTSC tapes, where a layer 5–8 μm thick of the superconducting composition YBaCuO, GdBCO was deposited on a tape 40 μm thick and 4 mm wide made of steel S-276 (Ni-Cr-Fe) and coated with 3 microlayers of metals 3μAg, 4μCu, 4μPbSn (industrial brand SuperOx, manufactured by S-Innovations, Russia-Japan, www.superox.ru) [14]. 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 the surface of (1102) Al_2O_3 at T_s=750 °C, which had critical values T_c=88–90 K and $J_c > 10^6$ A/cm^2 (77 K) [15].

Electron exposures. 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 at the Elektronika U-003 accelerator from a fluence of 10^{14} el/cm^2 (time 40 sec) to 5×10^{14} el/cm^2 (time 200 sec), a current of 400 nA and a fluence of 10^{15} el/cm^2 (time 160 sec) at a current of 1 mA.

Gamma irradiation. The samples were irradiated with γ-quanta (1.17 and 1.33 MeV) of the ^{60}Co isotope at a power of 65 R/s in the dose range of 10^5–10^6 R in the superconducting state when immersed in liquid nitrogen (77 K).

Experimental technique. The magnetic characteristics were studied using the Hall effect measurement method in the application of a magnetic field of 0.556 Tesla in the temperature range of 80–320 K, including the superconducting transition, using the Hall Effect Measurement System (HMS-7000). The samples were cut out in the form of strip pieces 2–5 cm long and 4 mm wide. The contact switching diagram in the Hall cell is shown in the figures below 4.

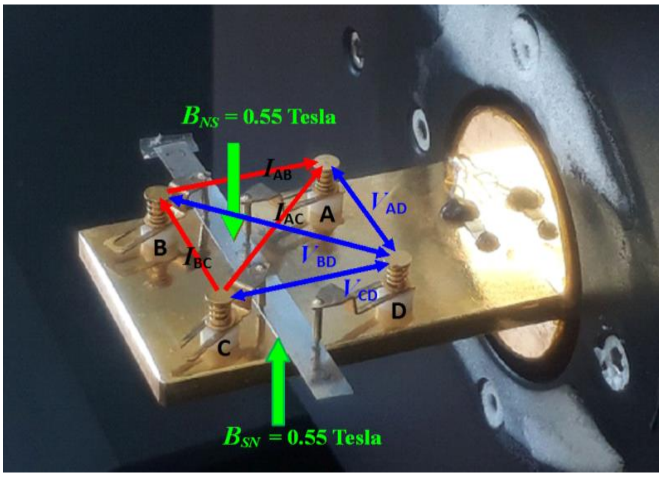

Fig.4. Measuring cell with 4 gold-plated contacts A-B-C-D pressing the sample, arrows indicate the directions of the electric V and magnetic B field of 0.556 Tesla, as well as the current I

Results and its discussion

In Fig. 5 shows the temperature dependences of the magnetoresistance R of YBaCuO tape samples before and after irradiation with three electron fluences in the range 80–320 K, including T_c around 90 K.

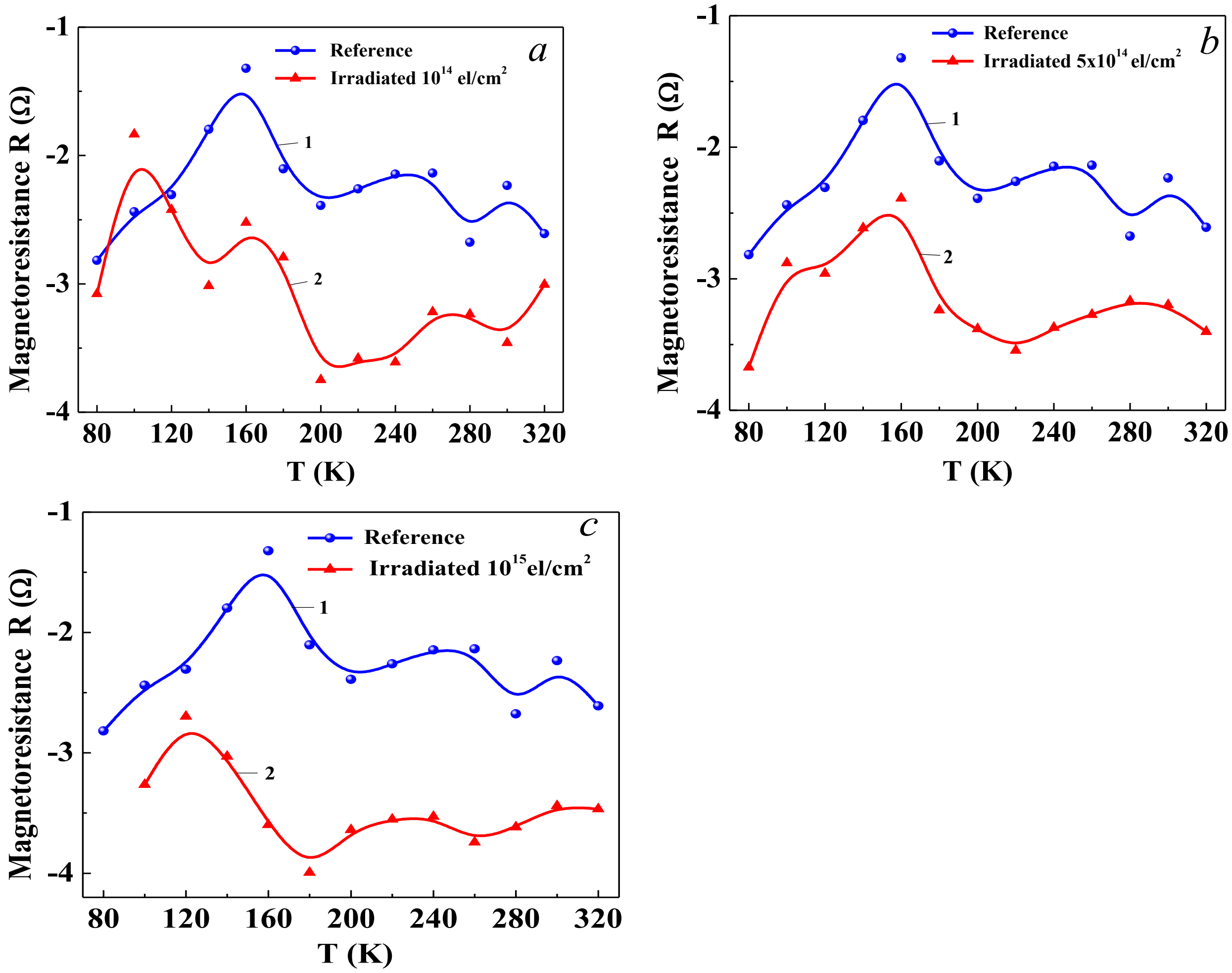

Fig.5. Magnetoresistance of YBCO tape after irradiation at 5 MeV electrons in air:

1 – reference, 2– (a)- 10^{14} el/cm^2; (b)- 5×10^{14} el/cm^2; (c)- 10^{15} el/cm^2

The main effect of electron irradiation is a significant (by more than an order of magnitude) reduction in magnetoresistance and a sharper superconducting transition below 100 K compared to an unirradiated standard. After the electron irradiation to 10^{14} cm^{-2} the superconducting transition becomes steep below the onset at 100 K, while the peak at 150 K decreased 10 times (Fig.5. (a) curve 2). It was found that magnetoresistance peaks in the range of 80–320 K after irradiation decrease by 10 times (Fig.5. (b) curve 2). As can be seen, the decrease at 120–160 K and 230 K indicates the formation of magnetic flux pinning centers, second-order phase transitions from a normal metal to a mixed magnetic state, and then to a superconducting state. A deep minimum appears below mΩ at 200 K, which has the magnetoresistance lower than that at 80 K (below T_c) in the non-irradiated sample and maybe due to paramagnetic-to-diamagnetic transition. Since the tape contains antiferromagnetic Cu and ferromagnetic Ni-Fe microlayers, the occurred peaks in 250–320 K relate to them and correspond to various PC.

In Fig. 6 shows the temperature dependences of the magnetoresistance R of GdBCO tape samples before and after irradiation with three electron fluences in the range 80–320 K, including T_c around 90 K.

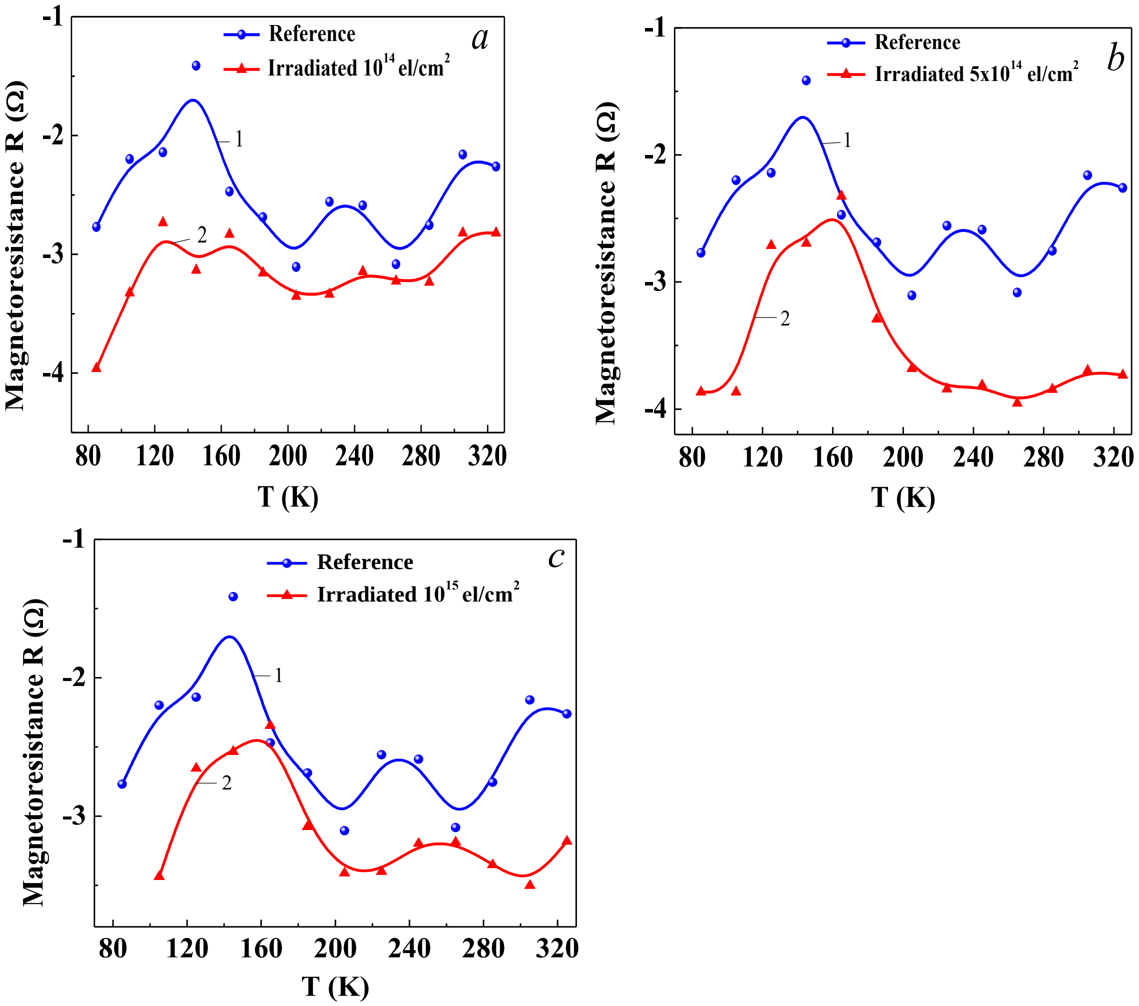

Fig.6. Magnetoresistance of GdBCO tape after irradiation at 5 MeV electrons in air:

1 – reference, 2– (a)- 10^{14} el/cm^2; (b)- 5×10^{14} el/cm^2;(c)- 10^{15} el/cm^2

fig.6 shows both magnetoresistance at applied H=0.556 Tesla parallel to c-axis and current carrier mobility decreased significantly, while the superconducting transition T_c was at ~90 K and the strongest pinning occurred at 265 K. Thus, the electron energy 5 MeV turned out enough for penetrating all coatings and damaging the HTSC layer. Within 80–320 K the tape is in mixed magnetic states of GdBCO and Ni-steel substrate, thereby providing effective flux pinning by highly correlated non-superconducting state.

Fig.7 show the magnetoresistivity of the non-irradiated and γ-irradiated samples at 77 K.

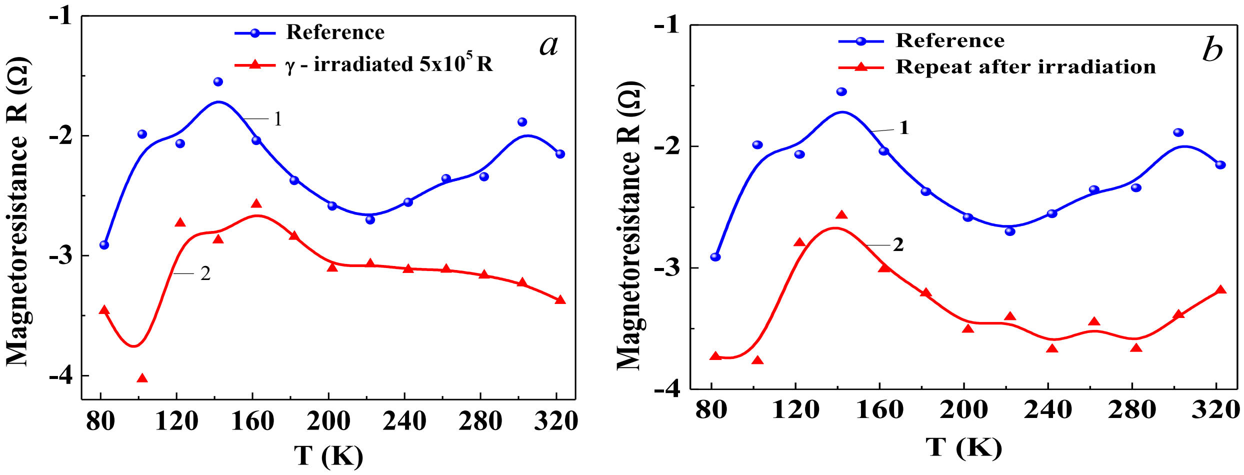

Fig.7. Hall-effect measurements of YBCO-tape: Magnetoresistance R (Ohm), a) 1 – Reference, 2 – ^{60}Co γ-irradiated to 5×10^5 R at 77 K; b) 1 – Reference, 2 – Repeated measurements from 80 to 320 K to release charged carriers from traps

Highly penetrative 1.17 and 1.33 MeV γ- quanta emitted from long-living ^{60}Co radionuclide can excite every nuclide and generate electron-positron pairs (511 keV), therefore it is believed effective in producing structure defects in all layers and the related PC. The dose rate (gamma flux) 65 R/s equals to 5.85×10^{11} quant/cm^2 s and can produce primary defects spaced ~200 nm, which is a bit more, than the Lorentz length λ_{ab}=140 nm estimated for YBCO in [16]. In the non-irradiated tapes the maximal magnetoresistance ~0.1 Ohm occurs at 160 K for YBCO and 140 K for GdBCO. After the irradiation at 77 K there emerges a giant magnetoresistance (~10^6 times growth) below 250 K (YBCO) and 200 K (GdBCO), [17] attributes it to triplet bipolarons. The width of such an ordered paramagnetic phase transition to a non-magnetic disordered state is ~10 K. At 77 K the coherence length increases and basic magnetic pinning may dominate the core one. Such irradiation imitates operation conditions in accelerator.

Conclusions

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. 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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