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Rare earth element influence on growth rate and critical current of high temperature superconducting tape

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Samples of coated conductors based on $RE\mathrm{Ba_2Cu_3O_{7-x}}$, where RE denotes Y, Gd, Sm, Eu, Dy, have been studied. The superconducting layer was deposited by PLD method on steel substrate with textured layers of YSZ and CeO_2. The lower the melting temperature of the corresponding rare-earth element, the higher the rate of formation of the HTS layer. It was found that in a perpendicular magnetic field at nitrogen temperature the critical current increases in the series Y → Dy → Gd → Sm, while at helium temperature this trend is reversed.

Keywords: REBCO, rare earth element, critical current, anisotropy.

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1. Introduction

It is generally accepted that second-generation high-temperature superconducting tapes (coated conductors) based on the compound $RE\mathrm{Ba_2Cu_3O_7}$ (REBCO), where RE is a rare earth element, are one of the key elements of the transition to resource-saving energy [1]. However, despite the extraordinary efforts spent, the production of fairly cheap coated conductors with high performance characteristics remains an unsolved problem [2]. One commonly used option for varying performance is to replace the standard yttrium in REBCO with another rare earth element or a combination of REs [3–7]. At present, the literature lacks comprehensive studies that explore the impact of rare earth elements on the properties of coated conductors. The matter is complicated by the fact that the multifactor manufacturing process does not allow direct quantitative comparison of the results of different authors, even in cases where similar technologies were used.

In such a situation, identifying qualitative trends in REs influence, confirmed by many scientific groups, regardless of the technology used, is of particular value. This paper presents the findings of research conducted on various coated conductors samples. The RE elements used in the study were Y, Dy, Gd, Eu, and Sm.

2. Experiment

The targets were manufactured at JSC „VNIINM“ using oxalate coprecipitation, microwave drying, pyrolysis, high-temperature treatment and pressing. This method allows to obtain targets with a given form factor and with a density of more than 90% of the theoretical one [9,10]. Details of the target preparation method are given in the paper [11].

All coated conductor samples were manufactured on a pilot production line at the National Research Center „Kurchatov Institute“ [12,13]. The manufacturing process of a long coated conductor tape (width 4 mm) consists of several successive stages [14]. Two of them are key stages for this paper. First stage is the stage of REBCO layer formation using pulsed laser deposition. At this stage, for all REBCOs, the following were kept fixed: oxygen pressure (100 mTorr), energy and frequency of laser radiation (600 mJ, 200 Hz), as well as the speed of the tape when passing through the growth chamber (36 m/h). The temperature of the substrate heater was varied in the range from 990 to 1020°C, in order to maximize the critical current at 77.4 K in self-field. Second key stage is annealing in an oxygen atmosphere (850 mbar) at a temperature of 450°C for 4 h and slow cooling to room temperature with the oven. This stage was the same for all samples.

The critical current was determined according to the criterion 1 μV/cm, achieved on the current-voltage curve (CVC) with standard transport measurements using the four-terminal method. The angular dependences of the critical current $I_c(\theta)$ were measured in the so-called. maximum Lorentz force configuration: the magnetic field is always perpendicular to the transport current. Angle θ was measured from the plane of the tape. The study of angular dependences was carried out in liquid nitrogen (77.4 K) at atmospheric pressure in an external magnetic field of 1.5 T. Measurements of the critical current in liquid helium (4.2 K) were carried out with the external magnetic field oriented normal to the tape.

The critical temperature was determined by the inductive method at a frequency of 30 Hz. The temperature value at which 50% of the signal in the normal state is reached was recorded on the transition curve. This value was taken as the critical temperature T_c.

3. Results and discussion

Figure 1, *a* shows the dependence of the REBCO critical temperature T_c on ionic radius RE r^{RE} (valency 3+, coordination number 8). For different REBCO compositions the critical temperature T_c varies from 89.9 to 93.0 K. A linear dependence T_c on r^{RE} is visible, which was previously noted by many authors both for coated conductors [4] as well as for bulk materials [15]. Deviations from the linear dependence can be explained by the fact that REs with large ionic radii tend to replace barium [6,16], and, accordingly, to reduce T_c, and also by not optimized for each RE oxygenating heat treatment [5].

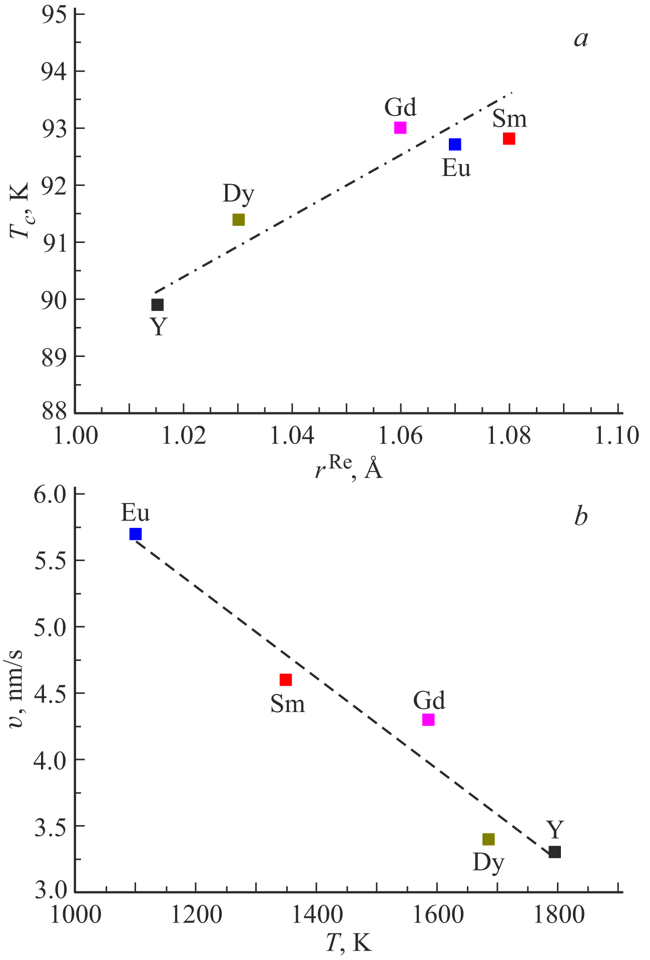

Figure 1. *a*) Correlation of critical temperature and ionic radius of rare earth elements. *b*) Correlation of the formation rate of HTS layer and the melting temperature of the corresponding rare earth element.

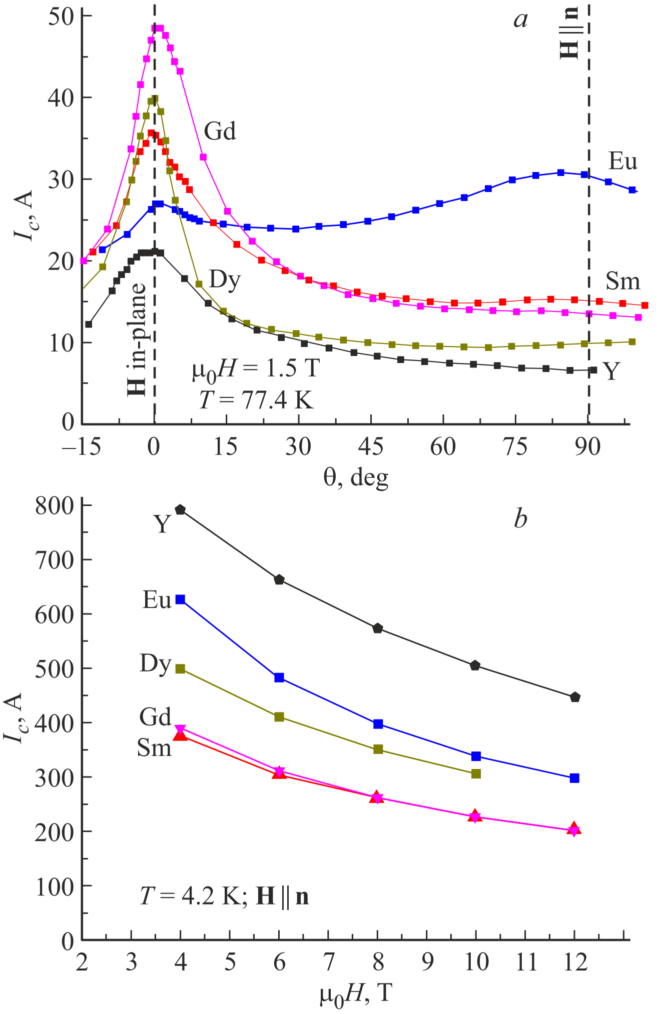

Figure 2. *a*) Angular dependence of the critical current $I_c(\theta)$ at 77.4 K in external field $\mu_0 H = 1.5$ T. *b*) Field dependence of the critical current at 4.2 K and the orientation of the magnetic field normal to the tape.

One of the most important parameters from the point of view of the economics of coated conductor production is the deposition rate. It was found that the growth rate varies by more than 1.5 times for different REs. In contrast to the paper [3], we noted an inverse correlation of the growth rate with the melting point of the corresponding RE (Figure 1, *b*), but not a direct correlation with the size of the ionic radius. The lowest melting point of europium leads to high diffusion mobility, which in turn leads to a maximum growth rate of 5.7 nm/s. Another factor, that obviously influences the growth rate of the HTS layer, is the process of target sputtering as a result of interaction with laser radiation. However, in this paper no correlation was found between the deposition rate and any characteristic of the target, with the exception of the chemical composition.

Since the boiling point of liquid nitrogen (77.4 K) is close to the critical temperature of REBCO, it can be assumed that the value of the critical current I_c will be determined by the reduced temperature $t = T/T_c$, and, accordingly, it will be higher with the higher T_c and the larger ionic radius. However, this simple picture is significantly complicated by the fact that the magnitude of the anisotropy of the critical current I_c does not have a clear correlation with the size of the ionic radius (Figure 2, a) in contrast to the thermodynamic critical parameters , in particular H_{c2} [17]. Moreover, the critical current of EuBCO has an anomalous anisotropy: when magnetic field oriented normally, the current is higher than for in-plane orientation. With the exception of Eu, the least preferred magnetic field orientation for REBCO is normal to the tape. Notably, at nitrogen temperature the critical current $I_c(\theta = 90^\circ)$ increases in the series $\mathrm{Y} \rightarrow \mathrm{Dy} \rightarrow \mathrm{Gd} \rightarrow \mathrm{Sm}$ (Figure 2, a), and at helium temperature this sequence changes to the opposite (Figure 2, b). Similar trends were observed in the work [4] using a completely different deposition method.

4. Conclusion

Replacing the rare earth element in REBCO is a powerful tool to control the current-carrying capacity of coated conductors. The influence of RE is not limited to the dependence on the corresponding ionic radius. The main empirical observations made in the paper can be summarized as follows:

1. RE affects the rate of deposition of the HTS layer during laser ablation: the lower the melting temperature of the corresponding RE is, the higher the rate is.

2. The use of various RE makes it possible to control the degree of critical current anisotropy over a wide range. For the samples studied in this paper, the anisotropy value at nitrogen temperature varied from 0.9 to 4.0.

3. In a perpendicular magnetic field at nitrogen temperature the critical current increases in the series $\mathrm{Y} \rightarrow \mathrm{Dy} \rightarrow \mathrm{Gd} \rightarrow \mathrm{Sm}$, whereas at helium temperature this trend is reversed.

The latter observation indicates a significant difference in the temperature dependences of the critical current of different REBCOs. Each REBCO composition can find its own area of application, since it is optimal for specific operating conditions, determined mainly by the ranges of operating fields and temperatures.

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Conflict of interest

The authors declare that they have no conflict of interest.

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