Effect of picosecond laser exposure on the transport characteristics of second-generation HTS tapes

S V Pokrovskii, O B Mavritskii, A N Egorov, N A Mineev, A A Timofeev, I A Rudnev

National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe sh. 31, 115409 Moscow, Russia

E-mail: sergeypokrovskii@gmail.com

Abstract. The main purpose of the work is to improve the magnetic and transport characteristics of 2G HTS tapes by creating an ordered array of artificial pinning centers. Using a picosecond laser exposure, a local modification of the HTS film were performed. The pulse energy varied from 300 to 4000 nJ, the pulse duration was 25 ps. A triangular array of micron size defects with a period of 50 μm was created. The dependences of the critical current and $n$-value change on the pulse energy were obtained. The parameters of the exposure resulting in an increase of the HTS tape critical current and tune of the $I-V$ characteristic slope were found.

1. Introduction

The work is devoted to the investigation of the modification of high-temperature superconductor (HTS) GdBa$_2$Cu$_3$O$_{7-δ}$ thin film using picosecond laser exposure. The main goal is to increase the magnetic and transport characteristics of the second-generation (2G) HTS tapes by creating an artificial pinning centers array. There are many papers describing researches and methods of artificial pinning centers creation in superconducting materials in literature. Most of them is devoted to the study of bulk superconductors or thin films on the single-crystalline substrates. In that cases an array of pinning centers is obtained by drilling the superconducting material, by irradiation or by addition of nonsuperconducting nanopowders [1-3]. The typical size of one element is of the order of several nanometers. These techniques have a number of disadvantages such as difficulty to use for industrial tapes on metal substrates, high cost and inability to scale on long-length tapes. There are also works on the use of laser action to create pinning centers to fix the vortex structure in the superconductor [4,5]. However, in most studies low temperature superconductors (for example Nb) have been used as samples materials. The developed method allows us to perform a controlled change in the parameters of industrial HTS tapes and locally improve the current-carrying characteristics of the material.

2. Experimental method

While selecting the laser equipment for the experiment, the following considerations were taken into account. It is well-known, that the precise lasers micromachining is closely related to the use of laser radiation pulses with durations shorter than the time of electron-phonon relaxation. This time is material-dependent and has the order of 0.1-20 ps [6]. So, pico- or even femtosecond lasers are required for the processing with the minimal thermal load to the material.
The diameter of holes in the HTS film should be as small as possible (ideally tens of nanometers). For the TEM00 lasers working in the visible or near-infrared wavelength range, the respective focused beam diameter can be an order of wavelength, i.e., about 1 μm. To tightly focus the laser beam into the smallest spot, the high numeric aperture (NA) objective with minimum aberrations for the working wavelength must be used. The laser beam quality $M^2$ is also very important parameter, guaranteeing the beam distortions are small enough to get the best results.

The micromachining application requires the precise adjustment of the laser pulse energy, allowing to control the regime of material processing. For example, by slightly varying the energy near the threshold of the material damage, it is possible to get not a through hole, but a crater, providing specific defects that may exhibit some interesting properties. Also, the laser energy stability from pulse to pulse should be good enough to reduce the energy adjustment error.

It is desirable to position the focused laser beam on the HTS film of various sizes (up to 12 mm width) with highest possible accuracy. Typical accuracy values for commercially available translation stages are about 1 μm or better with travel ranges of 25…100 mm.

According to the mentioned above requirements, the experiments were made using FEMTO-T laser facility designed in NRNU MEPhI [7]. Figure 1 presents the general configuration of this facility, the main part of which is the AVESTA’s MPAP 2500 laser source. The output pulse frequency can be set from single shot with external firing (pulse-on-demand) up to 100 Hz.

![Figure 1. Schematic diagram of FEMTO-T laser facility.](image)

Femtosecond pulses of low energy are generated by TiF50 Ti:Sapphire master oscillator, pumped with second harmonic of built-in CW diode-pumped Nd3+:YAG laser. From the output of master oscillator, the pulses pass to the stretcher, which increases their duration up to 200 ps for further amplification. The amplification subsystem consists of regenerative amplifier (RA), combined with pulse picker, producing the output pulses with up to several hundreds of μJ with controlled frequency or in single shot mode. To pump the RA the additional frequency-doubled Q-switched diode-pumped Nd3+:YAG laser is used. After amplification, the output pulses’ duration is reduced in tunable compressor to the value necessary for specific application. Beam expander, located at the output of laser source, matches the laser beam diameter to the input pupil of the focusing unit.

Laser pulses from the laser source output travel through the variable attenuator to focusing unit. The maximum attenuation coefficient is as much as $10^5$, allowing to precisely adjust laser pulse energy on the object from tens of pJ to several μJ.
The focusing unit is a high-resolution optical microscope equipped with an input laser port, LED illuminator and a set of large working distance infinity corrected NIR objectives from Mitutoyo. The CCD camera, attached to the microscope, produces the images of the object surface and helps to target the focused laser beam. The minimum laser spot diameter on object surface is about 1.2 µm, that is very close to the optical diffraction limit for the working wavelength.

The three-dimensional translation stage is used to precisely move the object relative to the focused laser beam. Its maximum travel range in both horizontal (X and Y) directions is 100 mm, while in vertical (Z) direction travel range is 25 mm, with minimum step of 0.15 µm. Motion control is performed by step-motor controller connected to PC via USB interface. The same PC is also used to control laser source, variable attenuator, microscope illuminator and CCD camera.

3. Results and discussion
In this paper we used the second generation industrial HTS tapes of 12 mm width manufactured by SuperOx, Russia. Samples were pre-selected and prepared for study. First of all, silver layer has been partially removed from the samples, which allowed to perform laser exposure directly on the superconducting film. In addition, since the critical current of the tapes exceeded 300 A at 77 K in self field (SF), it was dangerous to perform transport current measurements and don't burn the samples without silver layer. We divided the tapes into 2 pieces and the samples critical current in the pieces was dropped to a value little less than 150 A. The critical current measurements were carried out before and after laser exposure in the same measurement conditions. To test the absence of degradation one sample was not subjected to modification and passed the whole set of measurements.

Using a picosecond laser exposure, a local triangular array of defects of ~ 1 µm size with a period of 50 µm was created in the samples. We used single pulse regime. Figure 2 shows a SEM photography of the modified area. When the radiation energy is increased from 300 to 4000 nJ, the defect size also increases from 3 to 16 µm. In addition, the elemental composition in the melt region was investigated. There were no significant changes in stoichiometry in comparison with the initial material (Figure 3).

![Figure 2. SEM photography of the modified area, E=500 nJ.](image1)

![Figure 3. Elemental composition in the center of the irradiated region.](image2)

We measured the current-voltage characteristics of the samples before and after the laser exposure (Figure 4) and used a typical approximation of the I-V characteristic using the power law function. Dependences of the critical current and the n-value of the I-V characteristics on the energy of the laser pulse were obtained (Figure 5).

The obtained dependences have a domed shape that indicates the existence of optimal pulse parameters for the maximum increase the critical current. In our work we have found two special points: 500
nJ (sample 5, single defect size - 8.072 µm) and 2000 nJ (sample 7, single defect size - 14.024 µm). At that parameters we achieved almost the same enhancement of the critical current, but sharpness of the $I-V$ curve changed in different way.

Figure 4. $I-V$ characteristics of HTSC tapes before and after laser exposure.

Figure 5. Dependences of the critical current (criterion 1 µV/cm) and the $n$-value of the $I-V$ characteristics on the laser pulse energy.

This behavior can be explained by a change in the pinning force of the material in the region of the laser exposure. We created defects of large size that can't play role of pinning centers but at the edges could be generated cracks or point defects that pin vortex system. On the other hand the edge of a big defects itself is a good pinning center. This leads to an increase the critical current and a change in the $n$-value. But since we damage the film material the effective width of the superconducting tape reduces and the critical current also decreases. Thus, it is possible additionally to tune slope of the $I-V$ curve. In more detail these questions will be considered in further works.

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References
[1] Noudem J G, Meslin S, Horvath D et al 2007 Physica C 463–465 301–7
[2] Swiecicki I, Ulysse C, Wolf T et al 2012 Phys. Rev. B 85 224502
[3] Palau A, Monton C, Rouco V et al 2012 Phys. Rev. B 85 012502
[4] Wang Y L, Latimer M L et al 2012 Phys. Rev. B 87 22050
[5] Welling Marco S, Wijngaarden Rinke J et al 2004 Physica C 404 410–4
[6] Breitling D, Ruf A, Dausinger F 2004 Proc. SPIE 5339 49–63
[7] Gordienko A V, Mavritskii O B, Egorov A N, Pechenkin A A, Savchenkov 2014 Quantum Electronics 44(12) 1173–8