Variation of critical current and $n$-value of 2G HTS tapes in external magnetic fields of different orientation

V V Sychugov$^{1,4}$, P N Degtyarenko$^{1,2}$, A V Ovcharov$^1$, S V Shavkin$^1$, V S Kruglov$^{1,3}$, A L Vasiliev$^1$, P V Volkov$^1$ and Yu M Chesnokov$^1$

$^1$National Research Centre "Kurchatov Institute", Akademika Kurchatova pl. 1, 123182 Moscow, Russia
$^2$Joint Institute for High Temperatures of Russian Academy of Sciences, Izhorskaya st. 13 Bd.2, 125412 Moscow, Russia
$^3$National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe sh. 31, 115409 Moscow, Russia

E-mail: sychugovvv@gmail.com

Abstract. The in-field orientation dependence of critical current and $n$-value in second generation high temperature superconductive tapes was investigated. The samples were manufactured by Metalorganic Chemical Vapour Deposition method with BaZrO$_3$ inclusions (SuperPower Inc.) and Pulsed Laser Deposition method (Bruker HTS). For samples of each kind of fabrication techniques we observed higher critical current value in the case of external magnetic field aligned along (or nearby) $c$-axis direction in comparison with one aligned along $ab$-plane. We analysed possible reasons for this effect. Angular dependences of the critical current and $n$-value were investigated. The microstructure images of superconductive layer of studied samples show tilt of BaZrO$_3$ nanorods in MOCVD sample and high density of structural defects for PLD sample.

1. Introduction
The development of high temperature superconductor tapes of second generation (2G HTS) allows implementation of the superconductors in the wider application areas. An extended research of the superconductivity phenomenon is necessary for development of more powerful conductors. It was proved [1-3] that addition of nanoparticles to superconducting material leads to great enhancing of flux pinning. In this paper in-field critical current behavior of 2G HTS tapes prepared by a Metalorganic Chemical Vapour Deposition (MOCVD) with the BaZrO$_3$ (BZO) inclusions (SuperPower Inc.) and Pulsed Laser Deposition method (Bruker HTS). For samples of each kind of fabrication techniques we observed higher critical current value in the case of external magnetic field aligned along (or nearby) $c$-axis direction in comparison with one aligned along $ab$-plane. We analysed possible reasons for this effect. Angular dependences of the critical current and $n$-value were investigated. The microstructure images of superconductive layer of studied samples show tilt of BaZrO$_3$ nanorods in MOCVD sample and high density of structural defects for PLD sample.

2. Experimental details
The microstructural and electrical properties of two types of commercial 2G HTS tapes produced by SuperPower Inc. (MOCVD technology with advanced pinning (AP), called below “MOCVD sample”)
and Bruker HTS (PLD technology, called below “PLD sample”) (see Table 1) have been investigated. We used the same equipment and the methodology as in [6] to investigate the influence of BaZrO$_3$ nanoparticles embedded into the HTS layer on the critical current value in external magnetic fields up to 1T at different orientations. Standard four-probe measuring method was used. $n$-value was calculated for each Voltage-Current Curve. All experiments were performed in the maximum Lorentz force configuration.

Table 1. The experimental samples.

|               | SuperPower | Bruker |
|---------------|------------|--------|
| Technology    | MOCVD      | PLD    |
| Width         | 4 mm       | 4 mm   |
| Thickness     | 0.1 mm     | 0.2 mm |
| $I_c(77K, SF)$| 104 A      | 69 A   |
| Stabilization | Copper     | Copper |
| HTS layer     | GdYBCO     | YBCO   |
| Doping        | BaZrO$_3$  | ------ |

Detailed microstructural analysis was performed using scanning/transmission electron microscope TITAN 80-300 TEM/STEM (FEI, US) with Probe-Cs corrector and EDX spectrometer (EDAX, US) operated at 300 kV in NRC “Kurchatov Institute”. Platelets were prepared by standard FIB procedure in a Helios (FEI, US) SEM/FIB dual beam microscope.

3. Results and discussion

Figures 1a and 1d show in-field behavior of the 2G HTS tapes, the external magnetic field ranges from 0.0625 T to 1 T, orientation angle ranges from -20 to 180 degrees. As seen in Figure 1a there are pronounced peaks on the critical current curves for both MOCVD and PLD samples. The angular dependence of the critical current is not symmetrical for the MOCVD sample. In this sample the main peak is not aligned along $c$-axis but deflects from it at about 10° degrees. Figure 1b shows that up to the magnetic field of 1 T both PLD and MOCVD samples do not reach maximum of flux pinning force that means the flux pinning force peak located in the higher magnetic field.

As seen on Figures 1a and 1d the maximum of critical current in both samples for the magnetic field along the $c$-axis direction exceeds the one along $ab$-planes. The ratio for $B = 1$ T is $I_{ab}(1 T)/I_c(1 T)=0.79$ for PLD sample, and is $I_{ab}(1 T)/I_c(1 T)=0.53$ for the MOCVD sample. Therefore, it is clear that even in 77K/1T the BZO columnar structures pin magnetic flux stronger than intrinsic pinning between $ab$-planes, probably because the intrinsic pinning is disturbed by columnar structures. Concerning the PLD sample with no inclusions we suppose that high density of the intrinsic defects such as stacking faults, grain boundaries and twin-boundaries are responsible for such in-field critical current angular dependence.

Figure 1f shows that for the MOCVD sample there are two distinct peaks in $n$-value corresponding to the magnetic field aligned along the $c$-axis and parallel to the $ab$-plane. The $n$-value behavior for the PLD sample differs. For the field value as low as 0.0625 T $n$-value has two distinct peaks for $n$-value angular dependence. There is just one $n$-value peak for the field range from 0.0625 T to 1 T, and there are no pronounced peaks in the $n$-value for the field of 1 T.
Figure 1. Field orientation dependence of the critical current, \(n\)-value (maximum Lorentz force configuration) \(\theta = B \cdot n\) (normal to the sample surface). Field dependence of the flux pinning force. (a)-(c) PLD sample, (d)-(f) MOCVD sample. For plots b) and e) plots were chosen as follows: local maxima of the critical current value, one local minimum and one point is equal to the local maximum for the \(ab\)-plane direction of magnetic field.

We used approximation model described in [7] to fit the in-field critical current data. Good agreement with periodical model with two peaks within 5% error margin was obtained.

Two TEM images of the YBCO layer cross-section of the PLD sample are presented in Figure 2. No inclusions were observed in the layer, but only the columnar YBCO grains with high density of grain boundaries and threading dislocations, which are aligned pinning centers along \(c\)-axis, which probably
could cause high critical current value in magnetic field aligned along c-axis. The exact reason for the increased critical current values needs further investigation.

![Figure 2. TEM images of the PLD sample cross section.](image)

In contrast, distinct columnar BaZrO$_3$ nanorods are clearly visible in the cross-section images of MOCVD sample shown in Figures 3 and 4. The lateral dimension of the BZO nanorods varies from 3 to 7 nm. Thus these nanorods should provide strong pinning for the magnetic flux aligned in parallel with main nanorods direction. It is noticeable from Figures 3 and 4 that BaZrO$_3$ nanorods have an average tilt of about 11° degrees relative to the substrate normal which is in good conformance with asymmetrical shape of $I_c$ graph shown in Figure 1d. The direction of the columnar defects coincides with the maximum of critical current. Thereby BaZrO$_3$ nanorods make main contribution to pinning force for MOCVD sample in the direction of the c-axis of the sample.

![Figure 3. TEM image of the MOCVD sample cross section.](image)

![Figure 4. The enlarged TEM image of the MOCVD sample cross section. Dimensions of BaZrO3 nanorods are 3 to 7 nm.](image)

4. Conclusions
Critical current and $n$-value of 2G HTS samples prepared by MOCVD techniques with BaZrO$_3$ doping centers and PLD techniques were systematically investigated at applied magnetic field up to 1 T. The orientation dependence of the critical current value of such samples showed two distinct peaks. In the MOCVD sample the main critical current peak is not aligned along c-axis but slightly deflects from it at about 11° degrees. The microstructural study of the samples showed that there are BaZrO$_3$ columnar...
nanorods which are tilted at the same value relative to the substrate normal. For the PLD samples TEM images show high density of grain boundaries which aligned in normal direction to the sample surface. Corresponded orientation dependence of critical current is symmetrical. For both kinds of samples $n$-value orientation dependence were calculated from Voltage-Current Curves. Pronounced differences in $n$-values demonstrate in general that vortex matter is essentially different for these two kinds of technologies.

Acknowledgments
The authors would like to thank management of NRC "Kurchatov institute" for support of this work. The TEM measurements were performed on equipment of Resource Center for electronic microscopy “Nanozond” in NRC “Kurchatov Institute”.

References
[1] Malmivirta M, Yao L D, Huhtinen H, Palonen H, van Dijken S and Paturi P 2014 Thin Solid Films 562 554-60
[2] Ding F, Gu H, Zhang T, Wang H, Qu F, Dai S and Cao J 2012 Journal of Alloys and Compounds 513 277-81
[3] Sueyoshi T, Tokita Y, Fujiyoshi T, Mitsugi F and Ikegami T 2015 Physics Procedia 65 137-40
[4] Majkic G et al. 2013 Applied Superconductivity, IEEE Transactions on 23(3), 6602605
[5] Abraimov D, Ballarino A, Barth C, Bottura L, Dietrich R, Francis A and Rossi L 2015 Superconductor Science and Technology 28(11) 114007
[6] Shuvalov D B, Barkalov K E, Lymar A V, Sychugov V V, Degtyarenko P N, Shavkin S V and Kruglov V S 2015 Physics Procedia 71 417-22
[7] Hilton D K, Gavrilin A V and Trociewitz U P 2015 Superconductor Science and Technology 28(7) 074002