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Nanostructured oxide thin films for sustainable development

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Abstract

In the effort to emancipate mankind from fossil fuels dependence and minimize the CO_2 emissions, efficient transport and conversion of energy is required. Advanced materials such as superconductors and thermoelectrics are expected to play an important role in sustainable science and development. We propose an overview of our recent progress on nanostructured thin films of superconducting and thermoelectric oxides. Superconducting properties of $YBa_2Cu_3O_x$ and thermoelectric properties of Al-doped ZnO are described in relation to preparation techniques, experimental conditions, substrates used, structure and morphology. We especially discuss a nanoengineering approach for the enhancement of energy transport and energy conversion efficiency of oxide thin films compared to their corresponding counterpart of bulk materials.

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1. Introduction

These days, mankind has been starting to face many difficult issues: energy problems, environmental problems, water shortage problems and so on. It is a common feeling that new advanced materials will play an important role in the current challenge to develop alternative and sustainable energy technologies to reduce considerably our dependence on nuclear and fossil fuels and eliminate greenhouse gas emissions [1, 2].

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In particular, superconducting [3] and thermoelectric [4] materials seem fit to solve the energy puzzle since they can provide efficient energy transport and conversion, respectively.

Superconductors can transport electrical current without dissipation if cooled down at the appropriate temperature. Superconducting bulks and single crystals are quite important for the study of the basic physical properties, however for practical applications, such as direct current transport or winding of magnets, development of superconducting wires and tapes is strongly required. In order to be disclosed to the practical applications (lossless current transportation, winding of magnets and so on), superconducting materials should possess not only T_c, but also J_c (critical current density) and pinning force ($F_p = J_c \times B$, where B is the external magnetic field) as large as possible to cover a wide range of intended applications. Introduction of nanosized artificial pinning centres (APCs) was widely used to strongly enhance J_c and F_p of high temperature superconductors (HTSC) like $YBa_2Cu_3O_x$ (YBCO, T_c = 92 K) in magnetic field [6, 7]. Main advantage of HTSC towards conventional superconductors like NbTi or Nb_3Sn is the possibility to use nitrogen (boiling point: 77K) instead of helium (boiling point: 4.2K) as coolant. Impressively, in the past ten years or so, the nano-engineering approach to control microstructure, distribution, concentration and dimensionality of APCs has been demonstrated to be a powerful tool to produce YBCO thin films with excellent performances. Comprehensive review on the state of the art characteristics of YBCO wires and tapes can be found in [8].

Thermoelectrics can convert heat into electrical energy without moving parts. Efficient, small and light-weight thermoelectric modules are instrumental for recycling waste heat in a wide range of temperatures: gases from industrial plants, car engines, and even domestic stoves. In order to improve the efficiency of the thermoelectric conversion, the adimensional figure of merit $ZT = \sigma S^2 \times T/\kappa$ (where σ = electric conductivity, S = Seebeck coefficient; T = temperature and κ = thermal conductivity) must be increased. To date, the best performance is given by alloys like Bi_2Te_3 or Sb_2Te_3, whose key feature is the presence of natural nanosized defects which act as efficient phonon scatterers for the depression of κ and the consequent increase of ZT [9]. On the other hand, oxides have been recognized as promising candidates for practical utilization as thermoelectric materials since they are more stable than metallic materials in oxidizing environments over wide temperature range [10]. Indeed, oxides possess important characteristics, such as their benign nature, abundant supply, and cost effectiveness. More recently, researchers start to focus of thermoelectric oxide thin films which are easier to be functionalized at the nanoscale with respect to the bulk oxides. Overview on the recent status of research on thermoelectrics oxide thin films can be found here [11].

This contribution will briefly highlight our recent progresses on high quality nanostructured films of superconducting and thermoelectric oxides with strongly enhanced properties for sustainable energy applications

2. Experimental procedure

A Lambda Physik KrF excimer laser (λ = 248 nm) was used for fabrication of $YBa_2Cu_3O_7$ (YBCO) superconducting thin films doped with $BaSnO_3$ (BSO), Y_2O_3 and BSO+Y_2O_3 on $SrTiO_3$ (STO) substrates. The Pulsed Laser Deposition (PLD) conditions were: energy density E = 5 J/cm^2, deposition temperature (T) = 800 ºC, oxygen partial pressure (pO_2) = 200 mTorr, repetition rate (f) = 10 Hz, substrate to target distance (d) = 60 mm. For the deposition of pure YBCO thin film, a pristine YBCO target was ablated for 6000 laser pulses while for YBCO films added with nanodefects, YBCO+BSO mixed targets (YBCO added with x wt% of the BSO phase, being x 2, 4, 6 and 8%) and YBCO+Y_2O_3 surface-modified targets (in this case a slice of Y_2O_3, which percentage of total target area is denoted as A%, is suck on the surface of the target for periodical ablation and A% was varied as 2.5, 5.44, and 9.22%) were used. YBCO+BSO+Y_2O_3 films were prepared in multilayer fashion, alternating YBCO+BSO and YBCO+Y_2O_3 layers by periodic switching of the two targets.

Superconducting transition temperature (T_c), J_c/B characteristics (T=77 K, $B//c$, B=0~9 T) and $J_c/B/\theta$ angular dependences (T =77 K, B = 1 T, being θ the angle between B and c axis of ther film) were measured by physical properties measurement system (PPMS, Quantum Design, USA). The thermoelectric 2%Al-doped ZnO (AZO) thin films were grown on STO, Al_2O_3 and fused silica substrates by the PLD technique using a Nd:YAG laser (λ = 266 nm). The PLD conditions were: E = 4.2 J/cm^2, T = 300-600 ºC, pO_2 = 200 mTorr, f = 10 Hz, d = 35 mm. 2 % Al was found as the best doping in bulk. The electrical conductivity versus temperature (σ–T) characteristic was measured by a conventional four-probe technique from 300 to 600 K with a homemade apparatus. The Seebeck coefficient was