$Hg_{0.8}Re_{0.2}Ba_2Ca_2Cu_3O_{8.8}$ Thick Film Produced by Laser Ablation

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***Abstract*— This paper describes the development of $Hg_{0.8}Re_{0.2}Ba_2Ca_2Cu_3O_{8.8}$ thick film prepared with a precursor $Ba_2Ca_2Cu_3O_{5+d}$ thick film, which was layered by Laser Ablation technique on $PrBa_2Cu_3O_7$ substrate. The precursor thick film was thermally treated under mercury atmosphere using an encapsulate quartz tube technique. DC critical current measurements below T_C determined the thick film superconductor current critical density as a function of temperature. The general behavior of the critical current density as a function of temperature confirms that the (Hg,Re)-1223 thick film has junctions type classified as superconducting-insulate-superconducting (SIS). After the critical current test the superconductor thick film has not shown any degradation or stoichiometry loss and its critical temperature has not changed after the test. Taken into account the critical current value of thick film as compared with the bulk sample, it was suggested that the procedure described here can be applied to build most electronic-type applications based on (Hg,Re)-1223 ceramic thick film.**

***Index Terms*—** (Hg,Re)-1223, fault current limiter, laser ablation, thick film.

I. INTRODUCTION

The development of devices to protect electrical systems has recently increased due to the need to improve stability and reliability of these systems [1]-[5]. Specific attention is given on the design and application of high-T_C superconductor (HTSC) materials. The advances in the synthesis procedure of polycrystalline HTSC materials have enhanced the development of Superconducting Fault Current Limiter (SFCL) devices [6]. In fact, the resistive current limitation uses a difference between an on-state (superconductor - zero resistance) with high critical current density and an off-state (normal) with high resistance. In its simplest concept, the resistive limitation is obtained by mounting the superconducting conductor in series with the line to be protected [7]. A fault current limiter makes use of the superconductor phase diagram [8]. The phase diagram is built as a function of the current density, J, temperature, T, and magnetic field, H. When these values for J, T and H are appropriate, it is expected that the material is in superconductor state, i. e., non-resistive. It is possible to bypass the superconductor surface and go to normal state changing the current, where the material loses

Brazilian Microwave and Optoelectronics Society-SBMO received 1 Sept. 2010; revised 15 May 2011; accepted 21 June 2011
Brazilian Society of Electromagnetism-SBMag *ISSN 2179-1074*

superconductive properties. Here, it is considered that the fault current is twice its nominal value, that is, the current is at fault regime as defined by Sokolovsky et al. [5]. Almost all SFCL devices are based on different transition characteristics – from superconducting to normal state – of different materials. Thus, there are several types of SFCL being proposed and studied [5], [6], [9]-[11].

Since 2004, our research group has investigated a small resistive Superconducting Fault Current Limiter (SFCL) device, based on $Hg_{0.8}Re_{0.2}Ba_2Ca_2Cu_3O_{8.8}$ or (Hg,Re)-1223 ceramic, intending to obtain in the future a SFCL prototype for protecting low-impedance and high-current systems. For practical applications, the procedure to make thick film of (Hg,Re)-1223 ceramic T_c = 135 K is an important subject taken into account the few reports about this type of thick film. This compound is the best candidate for the technological applications at liquid nitrogen temperature (77K), considering that the expected operational temperature of the envisaged applications is $T_{use} \cong T_{c/2}$ (66K for Hg.Re-1223), whereas for most electronic-type applications the temperature of operation is $T_{use} \cong 0.7\ T_c$ (102K for Hg,Re-1223).

In this paper, it was investigated a critical current density behavior of $Hg_{0.8}Re_{0.2}Ba_2Ca_2Cu_3O_{8.8}$ thick film produced by Laser Ablation technique in order to obtain a SFCL prototype to protect a low impedance and high current system.

The simplest resistive SFCL contains an active superconducting element that is connected in series with a circuit that must be protected during fault current conditions. Fixing the temperature and magnetic field, if the current in the circuit increases and is higher than critical current the transition from superconducting state (zero resistance) to normal state (finite resistance) is triggered. The resulting resistance limits the fault current in this protected circuit and it is independent of field and current density, as ordinary conductors.

II. EXPERIMENTAL PROCEDURES

A. *Thick film synthesis procedure*

The ceramic precursor was prepared by mixing $Ba_2Ca_2Cu_3O_x$ (99,0% Praxair) and ReO_2 (99.0% Aldrich) in powder form with molar relationship of 1:0.18. The mixture was homogenized in an agate mortar and palletized with a pressure of 0.5 GPa. The pellet was annealed at 850 °C in a flow of oxygen of 15 h. The precursor obtained was crushed, homogenized and compacted again and annealed a second time at 930 °C for 12 h in an oxygen flux.

The procedure to deposit the superconductor thick film over $PrBa_2Cu_3O_7$ substrate begins with the precursor thick film deposition that was layered using Laser Ablation technique. The laser bean attack angle was 30º in relation to the target and the ceramic substrate was placed in front of the target, as can be seen in the Fig.1.

Brazilian Microwave and Optoelectronics Society-SBMO received 1 Sept. 2010; revised 15 May 2011; accepted 21 June 2011
Brazilian Society of Electromagnetism-SBMag ISSN 2179-1074

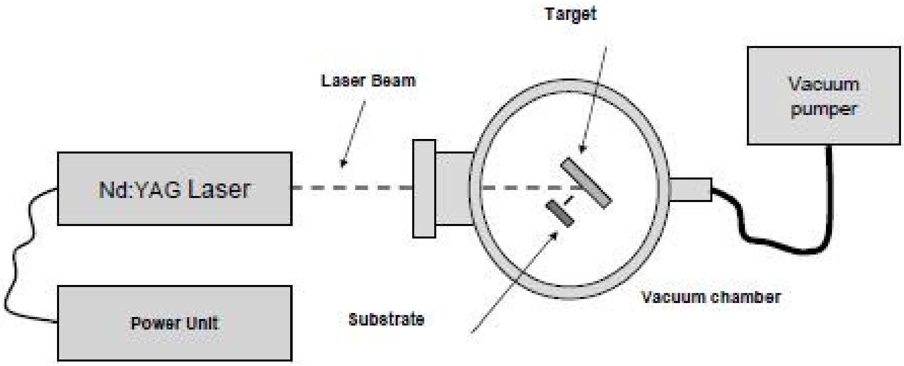

Fig. 1 - The set up presented a Nd:YAG laser (Quantel model Brillian b) at 1064 nm and a vacuum chamber.

The distance between target and substrate was 10 mm and the spot sizes of the laser beam 2 mm diameter. It were used 125 up to 200-shot pulses at 10 Hz to evaporation the compound precursor. The energy level was reduced down to 30 ± 10 mJ in order to avoid the precursor decomposition. Four different thick precursor samples were prepared. Four thick films of precursor were produced using 125, 150, 175 and 200-shot pulses at 10Hz.

Finally, the layered thick films precursor were wrapped in a 99.999% gold foil and introduced in a 8mm inner diameter quartz tube together with 60mg of HgO. The precursor thick films were thermally treated under mercury atmosphere (encapsulated quartz tube technique). In order to improve the grain growth, the annealing time was changed to 72 h at 865^{o}C, as compared to Sin *et al.* [12]. All details of the synthesis process and sample characterization of polycrystalline ceramic samples were reported by the references [14]-[16]. The final deposited thick films were analyzed by X-ray diffraction conventional machine RIGAKU Ultima_IV using a CuKα radiation in 2θ Bragg-Bretano symmetry.

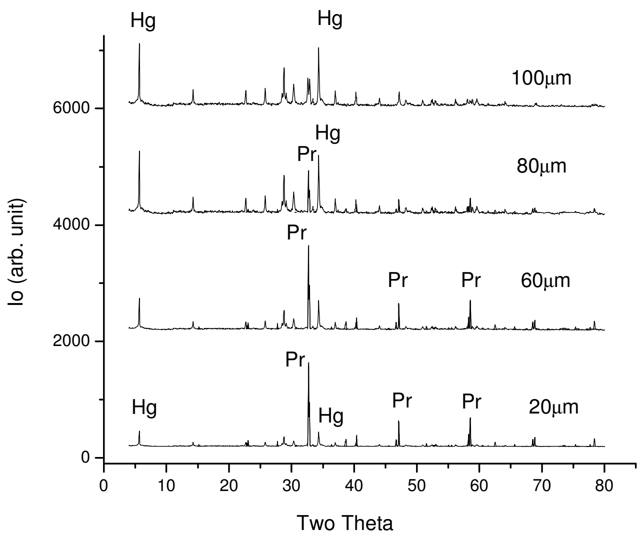

Fig. 2 - (Hg,Re)-1223 thickness evaluation. The $PrBa_2Cu_3O_7$ substrate (Pr) peaks reduce as a function of increase of the (Hg,Re)1223 superconductor thick film deposited.

Brazilian Microwave and Optoelectronics Society-SBMO received 1 Sept. 2010; revised 15 May 2011; accepted 21 June 2011
Brazilian Society of Electromagnetism-SBMag ISSN 2179-1074

A second analysis of deposited thick films were performed by Synchrotron X-ray diffraction technique at Laboratório Nacional de Luz Síncrotron - LNLS - Campinas- Brazil, and the results show that the best thick film presented about 100 ± 20 μm. This best thick film has used 200-shot pulses at 10 Hz to evaporation the compound precursor.

B. Critical current of the thick film

The DC critical densities of the current measurements versus temperature were performed in a best thick film (100 ± 20 μm) optimally oxygen-doped sample with 0.01x0.5x1 cm^3 dimensions. Four contacts, made of gold wire, were attached with silver paint on the surface of the polycrystalline sample ($R_{contact} = 2 \pm 1\ \Omega$). Two contacts situated at both ends of the sample were used to apply the current along the longitudinal axis whereas the voltage was measured using the other two contacts placed between the former ones. The current source was a KEITHLEY model 228A, and the voltage was measured by a KEITHLEY 182 sensitive digital voltmeter. For all temperatures, the critical current density J_c was defined using 10 μVmm^{-1} as electrical field criterion. The V-I curves were measured reversing the current direction to suppress any voltage drop due to contact resistance. The temperature of the sample was measured by a copper-constantan thermocouple attached to the sapphire sample holder and connected to a HP 34401A multimeter.

III. EXPERIMENTAL RESULTS

The Fig.3 presents a current density versus temperature behavior of $Hg_{0.8}Re_{0.2}Ba_2Ca_2Cu_3O_{8.8}$ thick film for limited temperature range.

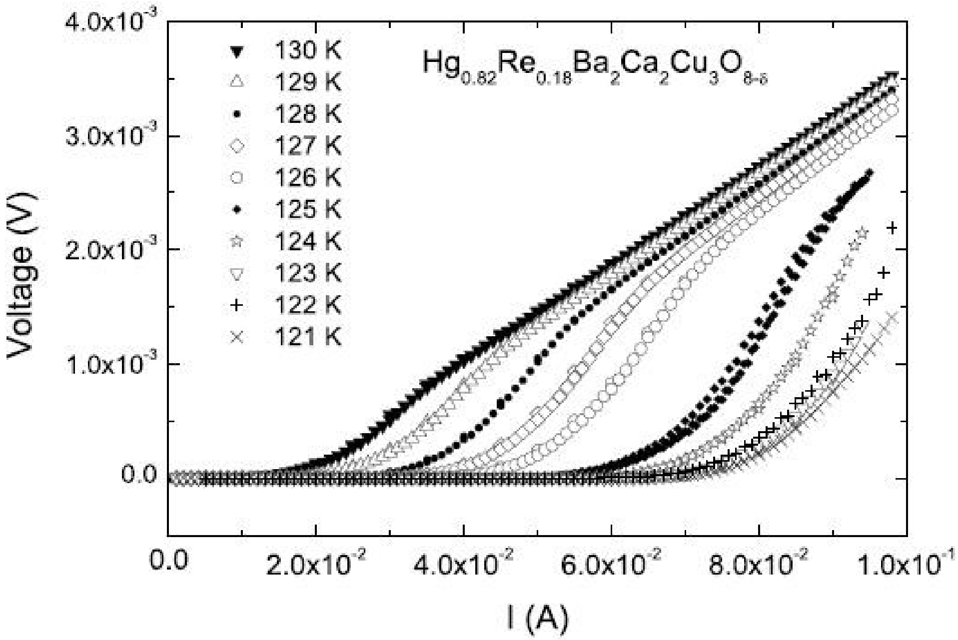

Fig. 3 - The voltage was measured by a HP34401A and KEITHLEY model 228A.

Brazilian Microwave and Optoelectronics Society-SBMO received 1 Sept. 2010; revised 15 May 2011; accepted 21 June 2011
Brazilian Society of Electromagnetism-SBMag ISSN 2179-1074

For 77K to 135K temperature range, the critical current density J_c was defined using 10 μVmm^{-1} as electrical field criterion. The results obtained for this range of temperatures are summarized in Fig. 4. According to the data, the critical density of current at 77K was $0.39x10^2$ A/cm^2.

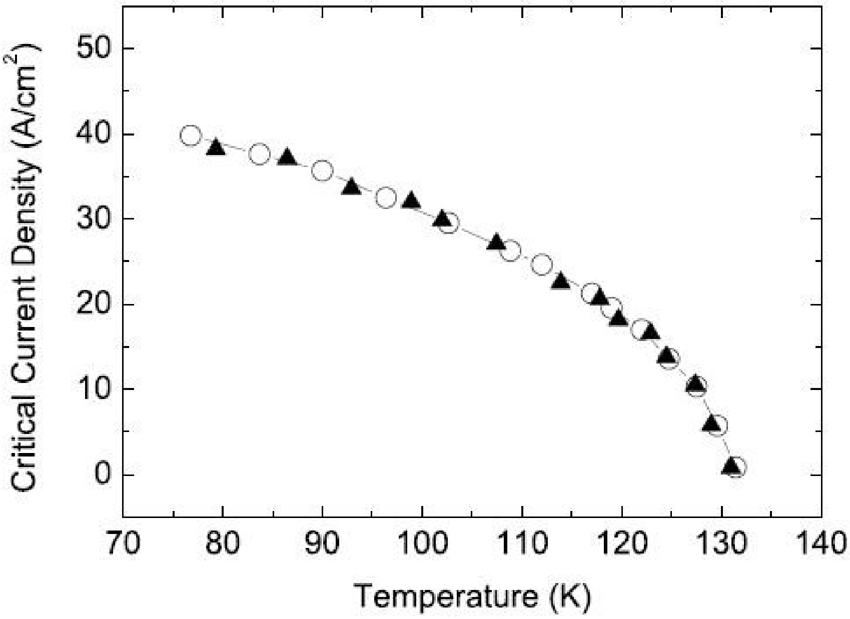

Fig. 4 - The critical current density Jc was defined using 10 μVmm^{-1} as electrical field criterion. The test was repeated two more times in 100μm thick Hg,Re-1223 film and the results are indicated by the triangle symbols. Circles represent the Jc results obtained to bulk samples of Hg,Re-1223 as ref. [16]

For practical applications, the critical current density J_c is one of the parameters that must be optimized for high-T_c granular superconductors (HTSC) [17]. The J_c of polycrystalline thick film superconductors is limited due to grain boundaries (intergrain regions) and defects within the grains (intragrain regions) such as point defects, dislocations, stacking faults, cracks, etc. [18]. The (Hg,Re)-1223 thick film shown a similar superconducting-insulate-superconducting (SIS) junctions [16] as found in the (Hg,Re)-1223 bulk ceramic. The critical current density J_c behavior in the Fig. 4 reveal there is not any improve of the thick film as compared with bulk samples. As considering only superconductor fault current limiter devices applications, the thick film has no presented any advantage as compared with bulk samples of (Hg,Re)-1223 However, for most electronic-type applications the thick film based on (Hg,Re)-1223 (T_c = 135 K) present a highest operational temperature $T \cong 102$ K ($0.7T_c$).

As an example, one can applied this thick film as a cryogenic heterodyne receiver working as sub millimeter mixers used from 70 GHz up to 1.2 THz, with a good performance, taken into account its SIS (Superconductor-Insulator-Superconductor) junction characteristic [19]. It is important to state that (Hg,Re)-1223 thick film presents junctions of SIS type. This was also pointed out by Passos et al. for bulk ceramic [16]. Our test verified that superconductor thick film did not suffer any degradation and its critical temperature has not changed after the DC current test (Fig. 4).

IV. CONCLUSION

For the best of our knowledge, it was developed for the first time an $Hg_{0.8}Re_{0.2}Ba_2Ca_2Cu_3O_{8.8}$ thick film prepared with a $Ba_2Ca_2Cu_3O_{5+d}$ thick film precursor, which was layered by a Laser Ablation technique on $PrBa_2Cu_3O_7$ substrate. The precursor thick film was thermally treated under mercury atmosphere using an encapsulated quartz tube technique. The critical current measurements below T_c determined the thick film superconductor critical current density as a function of temperature. The general behavior of the critical current density as a function of temperature confirms that the (Hg,Re)-1223 thick film presents junctions type classified as superconducting-insulate-superconducting (SIS). The superconductor thick film did not suffer, after the critical current test, any degradation and its critical temperature has not changed after the test. It was verified that the mercury stayed in the sample, which shows that this type of device is viable to applications like superconductor fault current limiter. After the critical current test, the superconductor thick film has not shown any degradation or stoichiometry loss and its critical temperature has not changed after the test. Taken into account there is no improvement of the critical current density J_c value of thick film as compared with the bulk sample, it as suggested that the procedure described here can be applied to build most electronic-type applications based on (Hg,Re)-1223 ceramic thick film. As an example, it was suggested that this thick film can be applied in cryogenic heterodyne receiver working as coherent detection device of sub-millimeter mixers used from 70 GHz up to 1.2 THz.

ACKNOWLEDGMENT

We would like to thank the grants of CNPq: CT-Energ 504578/2004-9 and 471536/2004-0, and CAPES for financial supports. Thanks also to Companhia Vale do Rio Doce (CVRD), ArcelorMittal - Cia. Siderúrgica de Tubarão (CST). We gratefully acknowledge the contribution of National Laboratory of Synchrotron Light - LNLS, Brazil (XPD and XRD1 beam lines) for providing access to their facilities.

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