ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 20, No. 2. 2014

Fast Two-stage Protector Against Electromagnetic Pulse Based on Electroresistance Effect in Polycrystalline La-Sr(Ca)-Mn-O Films

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crossref http://dx.doi.org/10.5755/j01.ms.20.2.6325

Received 29 January 2014; accepted 29 March 2014

The electroresistance (*ER*) effect in polycrystalline films of $La_{0.83}Sr_{0.17}MnO_3$ and $La_{0.7}Ca_{0.3}MnO_3$ was investigated in the temperature range of (5 – 290) K using high power sub-nanosecond rise time electrical pulses with amplitude up to 1 kV. It was obtained that conductance vs. voltage dependences are nonlinear and could be well fitted by empirical formula $G = G_0 + G_\alpha \cdot U^\alpha$; where G is conductance, U is the voltage applied across the sample, G_0 is the conductance at low voltage, and G_α and α are the parameters related to the electrical transport mechanism. Parameters α for La-Ca-Mn-O and La-Sr-Mn-O were 1.5 and 1.33 respectively. It was obtained that there are two regions of the electroresistance vs. temperature dependence for both films: low temperature region where *ER* exhibits very slow dependence on temperature and high temperature region where *ER* significantly decreases with temperature. It was demonstrated that polycrystalline manganite films can be used for the development of protectors against short electromagnetic pulse (EMP), and fast two-stage protector operating at cryogenic temperatures (80 K) is proposed.

Keywords: strong electric field effects, electroresistance, manganites, thin films, protectors against EMP.

1. INTRODUCTION

The electromagnetic pulse (EMP) generated in free space by natural or artificial electromagnetic pulse sources, such as lighting, nuclear EMP or other intentional electromagnetic environments (IEME) can induce high-power over-currents in electronic equipment and damage its active electrical components [1]. In order to protect electronic circuits against short EMP (sub-nanosecond duration electrical transients), fast protectors are required. Moreover, the short EMP pulses can be bipolar, for this reason symmetrical protectors are needed. The existing protectors based on gas discharge plasma limiters, varistors, and other electronic switches are too slow due to their large intrinsic capacitance. Thus their response is limited to microseconds. It has to be noted that up to now these devices were not used for cryogenic electronics. It was demonstrated [2 – 3] that polycrystalline manganite films can be used for the development of protectors against fast EMP. In this paper, the two-stage protector operating at cryogenic temperatures (80 K) is presented. The protector is mounted together with coaxial transmission line which can be replaced by high temperature superconducting microstrip delay line.

2. EXPERIMENTAL DETAILS

The $La_{0.7}Ca_{0.3}MnO_3$ and $La_{0.83}Sr_{0.17}MnO_3$ films with thickness $d = (350 – 400)$ nm were deposited by a Pulsed Injection Metal Organic Chemical Vapor Deposition MOCVD technique [4] onto a polycrystalline lucalox (99.9 % Al_2O_3 + 0.1 % MgO) substrate having small dielectric constant. The surface morphology obtained by atomic force microscope demonstrated that depending on preparation conditions and chemical composition the polycrystalline films consist of crystallite clusters with average diameter ranging from 135 nm to 240 nm (see Fig. 1).

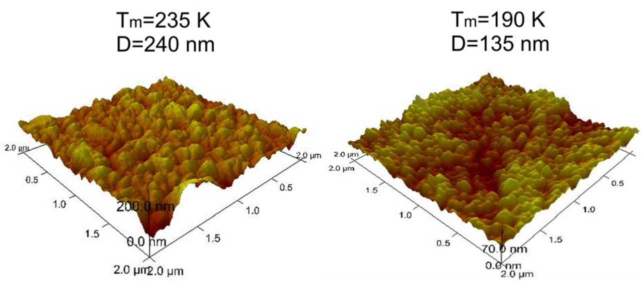
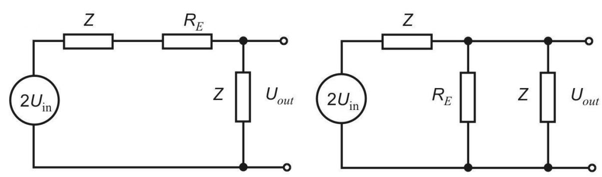


Fig. 1. Atomic Force Microscopy images of La-Sr-Mn-O (left) and La-Ca-Mn-O (right) films



a b

Fig. 2. Equivalent circuit for investigation of the *ER* of polycrystalline films (a) and transient characteristics of the protector (b). R_E is resistance of the sample, $2U_{in}$ is voltage from the generator, U_{out} is voltage measured across input impedance of oscilloscope $Z = 50\ \Omega$

The influence of strong electric field effects on the resistivity of polycrystalline films (electroresistance *ER*) was investigated using rectangular-shaped single pulses generated by a nanosecond generator (Kentech Instruments

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Ltd.) at temperatures from 5 K to 290 K. For this purpose the samples were connected in series to a 50-Ω-impedance 10 GHz bandwidth transmission line. The electrical pulses had a rise time of 150 ps and duration of 5 ns. The amplitude of these pulses ranged from several volts to 500 V. Equivalent circuit for investigation of electroresistance effect in polycrystalline films and transient characteristics of the protector are presented in Fig. 2, a and b, respectively.

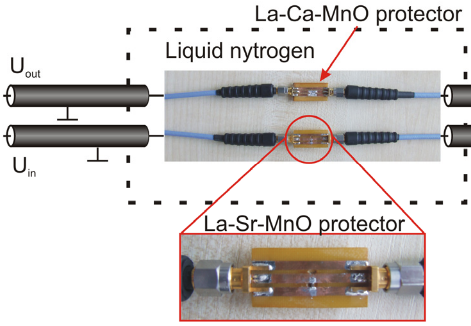


Fig. 3. Outside view of two-stage protector

The waveforms of input and output pulses were recorded with a DPO 71604C Tektronix oscilloscope. The limiting characteristics of a protector made from manganite film were investigated by mounting the sample in parallel to a 50 Ω impedance coplanar two-gap strip-shape transmission line. Fig. 3 shows the outside view of the two-stage protector consisting of La-Sr-Mn-O and La-Ca-Mn-O protectors.

3. RESULTS AND DISCUSSION

The investigation of conductance (G) vs. voltage across the sample (U) dependences performed on $La_{0.83}Sr_{0.17}MnO_3$ and $La_{0.7}Ca_{0.3}MnO_3$ thin polycrystalline films at temperature 80 K (see Fig. 4) had demonstrated that they can be well fitted using the following empirical formula [5]

$$G = G_0 + G_\alpha \cdot U^\alpha, \qquad (1)$$

where G_0 is the conductance at low voltage, and G_α and α are the parameters related to the electrical transport mechanism. The analysis of G vs. U dependences using formula (1) had demonstrated that non-linearity of it for $La_{0.7}Ca_{0.3}MnO_3$ films with parameter $\alpha = 1.69$ is higher than for $La_{0.83}Sr_{0.17}MnO_3$ films where $\alpha = 1.37$. Depending on parameter α value, different conductance mechanisms can take place in grain boundaries (GBs), i. e. when $\alpha = 1.33$ charge carriers are non-elastically tunneling through two localized states while when $\alpha = 2.5$ through three states in the GBs. It can be seen that in both polycrystalline films inelastic tunneling through two states is most likely taking place, although charge carriers in La-Ca-Mn-O films have higher possibility to tunnel through three states than in case of La-Sr-Mn-O films. It was obtained that at high amplitudes of electrical pulses the films were irreversibly damaged due to electrical breakdown. At temperature 80 K and pulse duration of 5 ns this breakdown appeared at 40 kV/cm electric field strength for $La_{0.7}Ca_{0.3}MnO_3$ films and at 100 kV/cm for $La_{0.83}Sr_{0.17}MnO_3$ films.

Fig. 5 demonstrates the electroresistance (ER) vs. temperature (T) dependences of the films exposed to different electric field strengths.

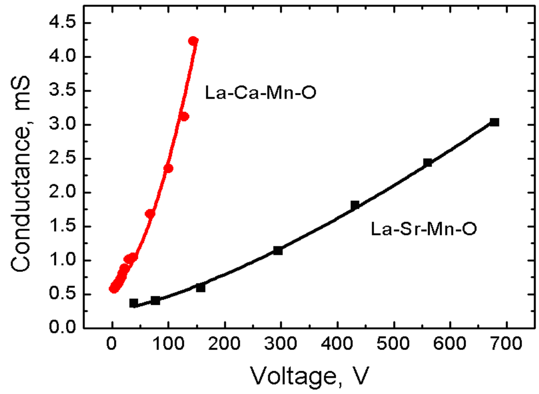


Fig. 4. Conductance vs. voltage across the samples of La-Ca(Sr)--Mn-O films

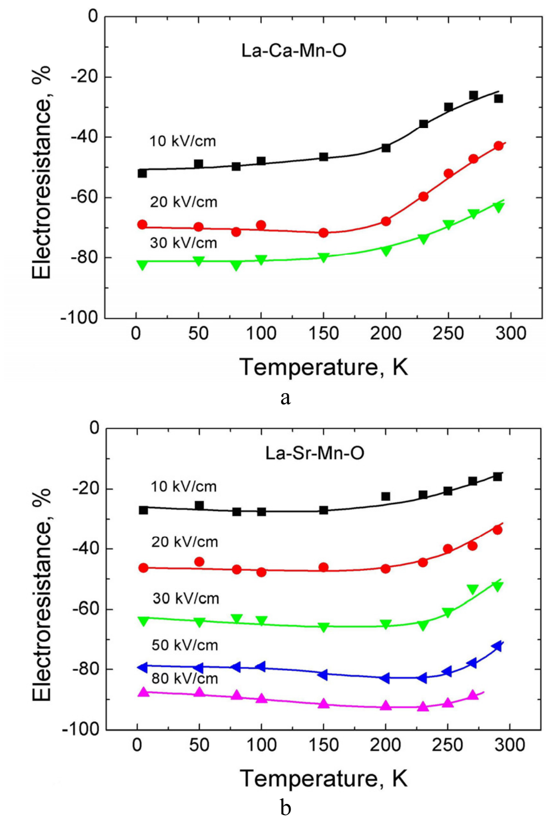
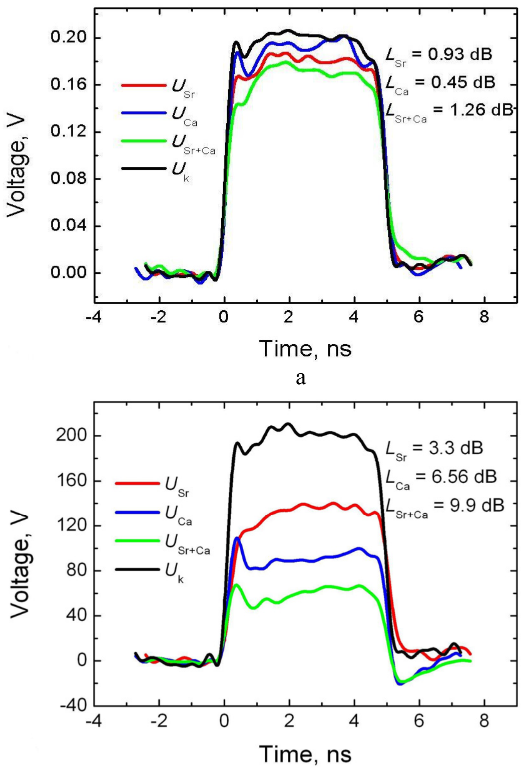


Fig. 5. Electroresistance vs. temperature dependences at different electrical field strengths for La-Ca-Mn-O (a) and La-Sr-Mn-O (b) films

The ER was defined as $ER = 100 \cdot [(R_E - R_0)/R_0]$, where R_E and R_0 are resistances of the film at high and low electrical field strength, respectively. As it can be seen for both films, it is possible to select two regions of ER vs. T dependence: low temperature region in which the electroresistance is high and exhibits very slow dependence on temperature and high temperature region where electroresistence significantly decreases with temperature. For $La_{0.7}Ca_{0.3}MnO_3$ the low temperature region lasts from 5 K to 190 K while for $La_{0.83}Sr_{0.17}MnO_3$ films this region lasts from 5 K to 240 K thus decreasing when aproaching transition from metal-like to insulatorlike state temperature T_m. Moreover, Fig. 4 shows that electroresistance at the same electric field strength is higher for $La_{0.7}Ca_{0.3}MnO_3$ films in comparison to $La_{0.83}Sr_{0.17}MnO_3$ ones (1.33 times at 30 kV/cm).



b

Fig. 6. Transient waveforms of La-Ca-Mn-O protector, La-Sr--Mn-O protector and two-stage protector operating at T = 80 K in non-limiting (a) and limiting (b) regimes

In order to investigate how La-Ca-Mn-O and La-Sr-Mn-O films could be used for designing of high-power protector agains EMP, the circuit presented in Fig. 3 was constructed. It consists of two protectors made from $La_{0.83}Sr_{0.17}MnO_3$ and $La_{0.7}Ca_{0.3}MnO_3$ films and 50 Ohm impedance 1.8 m length coaxial transmission line. The protector based on La-Sr-Mn-O film having less abrupt nonlinear voltage current characteristic and higher irreversible breakdown field was mounted in the input of 1.8 m length transmission line while protector based on La-Ca-Mn-O film with more abrupt voltage current characteristics and lower irreversible breakdown field was placed at the output of this line. Both protectors were cooled down up to 80 K using liquid nitrogen bath while transmission line was outside this bath at room temperature. Fig. 6, a and b, demonstrates the input and output pulse waveforms at non-protecting and protecting regimes, respectively. Fig. 6, a, shows that maximal attenuation at non-protecting regime of this circuit is no more than 1.26 dB while at protecting regime (see Fig. 6, b) the attenuation increases up to 9.9 dB. Thus the two-stage protector is able to induce significant attenuation in high frequency transmission line if fault current pulse rise time is of the order of sub-nanoseconds, and consequently can be used for protection against short EMP. It has to be noted that 1.8 meter long transmission line was used taking into account pulse length in order to separate in time pulse clammed by the first protector and incident to the second protector. Such cable could be easy replaced by small dimensions superconducting delay line [6]. As a result, the total size of two-stage protector could be diminished down to few tens of cm^3. In this case compact protector which could be used for protection of high speed cryoelectronic devices can be designed.

4. CONCLUSIONS

It was demonstrated that thin polycrystalline La-Sr(Ca)-Mn-O films exhibit electroresistance effect, which can be induced by strong electrical field pulses having amplitudes up to 100 kV/cm and sub-nanosecond duration rise time. As a result, the conductance vs. voltage dependences are nonlinear and the parameter of this nonlinearity α is found to be higher for La-Ca-Mn-O films in comparison with La-Sr-Mn-O ones. This gives a possibility to design a two-stage protector, in which for the first step of attenuation the film doped with Sr has to be used. For the second stage the films doped with Ca are preferable. Using these films connected in parallel and separated by 1.8 m length coaxial transmission line, a protector operating at 80 K temperature and able to withstand pulses with amplitudes up to several hundred volts was designed. In non-protecting regime this protector induces 1.26 dB attenuation while in protecting regime the total attenuation at incident pulse amplitude of 210 V was 9.9 dB. It has to be noted that such protector could be used together with microstrip superconducting delay line. This enables to decrease significantly the dimensions of the device operating at cryogenic temperatures.

Acknowledgments

This work was partly supported by the Research Council of Lithuania under grant MIP-062/2012.

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