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Thin Film Manganite–Metal Interconnection and "Loop Effect" Studies in CMR-Based High Magnetic Field Sensors

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The design, technology and main characteristics of Ag contacts as well as "loop effect" peculiarities of colossal magnetoresistance B-scalar high magnetic field sensor based on $La_{1-x}(Ca)Sr_xMnO_3$ films used for measuring high magnetic field pulses are presented.

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1. Introduction

It was demonstrated that the colossal magnetoresistance (CMR)-B-scalar sensor can be successfully used for high pulsed magnetic field measurements [1, 2]. The sensor is a two-terminal device with thin manganite film as material sensitive to magnetic flux density (B) magnitude. For such devices it is necessary that interconnection between electrode and thin film would be of low resistance with linear voltage–current characteristic. Moreover, the "loop effect" (LE) induced in circuit sensor–two current leads has to be much smaller than response to magnetic field. The "loop effect" depends on the time derivative of the magnetic field, and therefore, it sets an upper limit to the operational frequency of the device.

In this paper the properties of interconnection between thin Ag and $La_{1-x}(Ca)Sr_xMnO_3$ films and investigations concerning LE in CMR-B-scalar sensors are presented.

2. Experimental results and discussion

2.1. Interconnection Ag–$La_{1-x}(Ca)Sr_xMnO_3$

The thin Ag film contact areas were fabricated by thermal deposition of Ag charge placed in W melting-pot at $\approx 10^{-5}$ kPa vacuum. During Ag deposition the temperature of manganite film prepared by metalorganic chemical vapor deposition (MOCVD) technique on "Lucalox" substrate was 150–200°C. The thickness of Ag film was changed from 0.2 to 1 μm. After Ag deposition the samples were heated during 20 min in oxygen atmosphere at 420–450°C temperature. Ag-electrode areas have square shape (1 × 1 mm) and are separated in substrate plane at distance varying from 50 μm to 3 mm.

Investigation of contact resistance (R_c) vs. temperature (T) dependence in the range 25 ÷ 300 K was performed using "four-probe" method. Typical results of this investigation obtained on polycrystalline La–Ca–MnO_3 film are presented in Fig. 1.

Figure 1a shows that resistance $R = f(T)$ curves corresponding to manganite film (1) and Ag contact (2) demonstrate typical ferromagnetic to paramagnetic phase transition behaviour, however, the absolute value of contact resistance (R_c) is about 10^4 times smaller than total film resistance (R_f). Moreover, critical temperature (T_m) at which resistance has its highest value is about 50 K higher in case of R_c vs. T dependence. In order to clear up the nature of this phenomenon, simultaneously with deposition of contact areas, the surface of film was covered by ultrathin Ag film with thickness about 20 nm. After thermal annealing at the same conditions as contact preparation the resistance of manganite film

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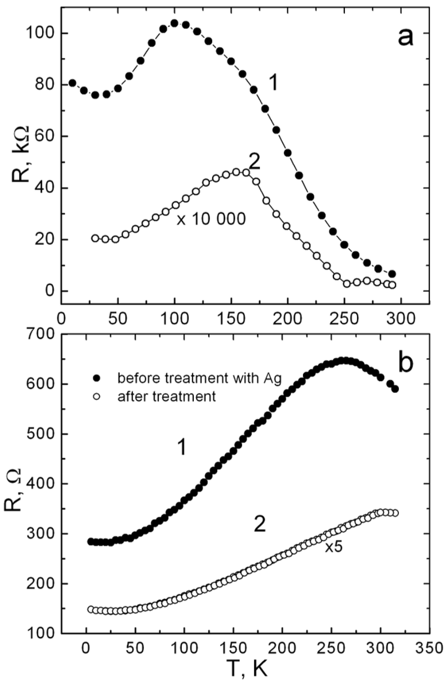

Fig. 1. Resistance vs. temperature dependence for La–Ca–MnO film (1) and Ag contact (2) (a) and for La–Sr–MnO film untreated (1) and treated by Ag (2) (b).

had decreased five times and T_{m} was shifted up to 50 K to higher temperatures (see Fig. 1b, curves 1 and 2).

The results presented in Fig. 1 show that Ag enables to create low resistance contact with La–Sr–MnO material. Thus it can be used for two-terminal resistive magnetic field sensor. From Fig. 1a it is evident that the interconnection between Ag and manganite film exhibits ferromagnetic to paramagnetic phase transition with lower resistance and higher T_{m} in comparison to the polycrystalline material. This can be explained assuming that Ag was introduced mainly at grain boundaries (GB) [3]. As a result, the net of GB are short-circuited at certain distance from the edge of Ag electrode. The region with short-circuited GBs has electric and magnetic properties similar to grain material with structure more perfect than GB. This assumption confirms experimental results obtained in [3] and presented in Fig. 1b. As can be seen, the significant decrease of resistance (10 times) and T_{m} shift ($\Delta T \approx 50$ K) to higher temperatures was obtained after introduction of small amount of Ag into La–Sr–MnO film.

2.2. "Loop" effect

The investigation of LE was performed using CMR-B-scalar sensor having effective area $S = 1 \times 0.05$ mm^2 and connected by 50 cm length twisted pair cable to the measurement circuit. The diameter of the wires and isolation thickness was 0.1 mm and 0.05 mm, respectively. The length of each loop was 2.5 mm. As magnetic field source the straight 10 cm length Cu lead carrying sinus waveform high current pulse was used. The sensor together with cable was placed near Cu lead at two positions: parallel and perpendicular to the lead. The LE was recorded as voltage transient (V_{L0}) at the beginning of the current pulse (see Fig. 2a).

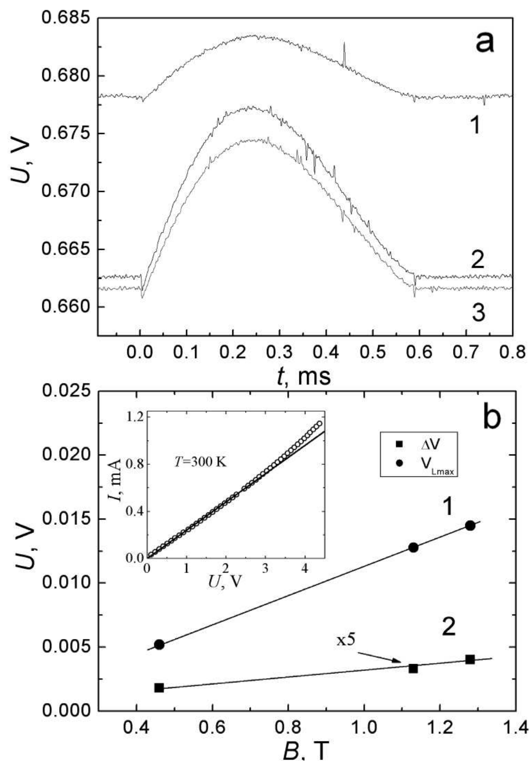

Fig. 2. Sensor's response to sinus waveform magnetic field pulses having different B_0: 1 — 0.46 T, 2 — 1.13 T, and 3 — 1.28 T (a). The ΔV and $V_{\mathrm{L\,max}}$ (×5) as a function of B_0 and DC voltage–current characteristic (inset) of sensor at 300 K temperature (b).

The highest value of V_{L0} was obtained when cable was in perpendicular position to the current lead due to non--homogeneous ($B \sim 1/x$, x is coordinate) magnetic field along the twisted cable. In case when cable was placed in parallel to the current lead the V_{L0} was approximately ten times less in comparison to the perpendicular position. For magnetic field pulse having half of sinus waveform ($B = B_0 \sin \omega t$, $\omega = \pi/T$, here T is pulse duration) the voltage induced by "loop" effect $V_{\mathrm{L0}} = B_0 S_{\mathrm{eff}}\, \omega \cos \omega t$ (S_{eff} is effective area of the "sensor–cable" system). The maximal value of this voltage $V_{\mathrm{L0\,max}} = B_0 S_{\mathrm{eff}} \omega$ appeared at time instant $t = 0$. At fixed B_0 and S_{eff} amplitude $V_{\mathrm{L0\,max}}$ depends on ω. If the sensor is supplied by DC current, the accuracy of the measurement depends on the ratio beween voltage change ΔV due to CMR effect and $V_{\mathrm{L0\,max}}$. For ±5% accuracy the ratio $\Delta V/V_{\mathrm{L0\,max}} = 10$. Nominating $\Delta V/B_0 = k_1$ and $V_{\mathrm{L0\,max}}/B_0 = k_2$, we obtained the following formula for calculation of maximal possible frequency ($f_{\max}$), which can be measured using CMR-B-scalar sensor

$$f_{\max} = 0.1(k_1/k_2)f_m\,, \quad (1)$$

where $f_{\rm m}$ is the fundamental frequency of the magnetic pulse, which was used for determination of coefficients k_1 and k_2. Figure 2b presents ΔV and $V_{\rm L\,max}$ as a function of B_0 obtained when voltage drop at the sensor was 0.8 V and $f_{\rm m} = 0.833$ kHz. The coefficients k_1 and k_2 calculated using data from Fig. 2b was 11.34 and 0.625 mV/T, respectively, that give $f_{\max} \approx 1.5$ kHz according to (1). The $f_{\max}$ can be increased biasing sensor by higher voltage, however this way has a limitation due to Joule's heating dissipated in magnetic material. In order to evaluate this heating we measured voltage–current characteristic (inset in Fig. 2b) of the sensor having dimensions $10^3 \times 50 \times 0.4$ μm^3 and obtained that up to ≈ 2.5 V the heating effect did not alter the resistance of the sensor. Thus using biasing by 2.5 V it is possible to increase $f_{\max}$ up to 5 kHz. Calculations using "loop" effect measurement data showed that effective area $S_{\rm eff}$ is of the order of 0.12 mm^2, while effective area of the sensor $S = 0.05$ mm^2. This demonstrates that S is about half of $S_{\rm eff}$, consequently small dimensions of the CMR-B-scalar sensor enables to design low effective area sensor–cable system, which can operate at accuracy $\pm 5\%$ or better up to 5 kHz without cable shielding.

3. Conclusions

It was concluded that thin Ag films can be successfully used as electrodes for CMR-B-scalar sensor design. The Ag mainly penetrates into the grain boundaries regions of the polycrystalline thin manganite film. The "loop" effect and heating of the thin manganite film by bias current limits the upper operation frequency of unshielded sensor up to several kHz.

Acknowledgments

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