Solid State Communications 248 (2016) 6–10

Contents lists available at ScienceDirect

Solid State Communications

journal homepage: www.elsevier.com/locate/ssc

Fast-track communication

Estimation of Joule heating and its role in nonlinear electrical response of $Tb_{0.5}Sr_{0.5}MnO_3$ single crystal

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ARTICLE INFO

Article history:
Received 11 June 2016
Received in revised form
30 August 2016
Accepted 9 September 2016
Available online 10 September 2016

Keywords:
Negative resistance
Resistance measurement
Magnetic oxides

ABSTRACT

Highly non-linear *I–V* characteristics and apparent colossal electro-resistance were observed in non-charge ordered manganite $Tb_{0.5}Sr_{0.5}MnO_3$ single crystal in low temperature transport measurements. Significant changes were noticed in top surface temperature of the sample as compared to its base while passing current at low temperature. By analyzing these variations, we realize that the change in surface temperature (ΔT_{sur}) is too small to have caused by the strong negative differential resistance. A more accurate estimation of change in the sample temperature was made by back-calculating the sample temperature from the temperature variation of resistance (*R–T*) data (ΔT_{cal}), which was found to be higher than ΔT_{sur}. This result indicates that there are large thermal gradients across the sample. The experimentally derived ΔT_{cal} is validated with the help of a simple theoretical model and estimation of Joule heating. Pulse measurements realize substantial reduction in Joule heating. With decrease in sample thickness, Joule heating effect is found to be reduced. Our studies reveal that Joule heating plays a major role in the nonlinear electrical response of $Tb_{0.5}Sr_{0.5}MnO_3$. By careful management of the duty cycle and pulse current *I–V* measurements, Joule heating can be mitigated to a large extent.

1. Introduction

Nonlinear electrical behavior and electric field induced changes in resistance (electro-resistance) in mixed valence manganites have been extensively studied. Different interpretations have been forwarded such as melting of charge order [1,2], modification of shape or percentage of phase separation by the current [3] (percolation phenomena) and formation of filamentary conduction channels [4,5]. Apart from these, Joule heating (JH) was attributed to be the cause of apparent colossal electro-resistance (CER) and negative differential resistance (NDR) in many systems [6–10]. JH is an undesired side effect resulting from electrical characterization and often depends on sample configuration and measurement protocol. Apart from the knowledge that JH often results in erroneous transport data, there have been very few attempts to rule out its contribution in transport measurements. Mercone et al. [7] have attributed the origin of nonlinear *I–V* data in bulk manganite to the temperature difference between sample and thermal bath. Nonlinear conduction was observed not only in bulk but also in thin film manganites, and calculations based on heat transfer across the substrate revealed the role of JH on transport characteristics over certain range of temperature and magnetic field [4,11,12]. Few researchers came up with analytical models based on concepts including Newtons law of cooling and polaronic conduction which satisfactorily explained current controlled NDR [7,13]. Most of the work related to the role of JH in NDR and CER observed in manganites are on charge ordered systems where the melting of charge order due to JH produces the nonlinear *I–V* curves [14,15]. Nonlinear *I–V* curves are also seen in non-charge ordered manganites with semiconducting/insulating properties, mainly because of JH [4,7,16]. Generally, estimation of JH is done by monitoring the temperature difference between the sample under investigation and the thermal bath. As pointed out by Mercone et al. [7], poor thermal conductivity and local heating of the material made monitoring the surface temperature difficult and prevented an accurate estimation of the JH particularly in bulk samples. In this report, we estimate and look at the role of JH in the nonlinear dc *I–V* characteristics of $Tb_{0.5}Sr_{0.5}MnO_3$ (TSMO50) single crystal which shows an overall semiconducting/insulating behavior. Both continuous and pulsed *I–V* measurements were carried out and the sample temperature is simultaneously measured. Temperature dependence of resistance (*R–T*) measurements were performed by applying very low current to avoid JH. JH was estimated by directly monitoring the sample temperature variation during measurements and by back-calculating the sample temperature from the *R–T* data.

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http://dx.doi.org/10.1016/j.ssc.2016.09.005

2. Experimental details

Single crystals of $Tb_{0.5}Sr_{0.5}MnO_3$ grown by optical float zone technique were used for dc resistance and *I–V* measurements between 50 and 300 K. *R–T* measurement was performed in pulse mode (pulse-off time = 1 s, pulse-on time 1 ms). Four silver point contacts are made on a parallelepiped sample (length l = 3 mm, width w = 2 mm, thickness t = 0.8 mm) and was thermally anchored to the cold finger of the closed-cycle helium refrigerator (CCR) using a thin layer of conducting GE/IMI-7031 varnish. The changes in the sample temperature (T_S) could be monitored by a PT 100 sensor glued on the top surface of the crystal using the same GE varnish. The base temperature (T_B) was measured using two silicon-diode sensors attached to the cold finger of the CCR which were positioned very near to the sample. A schematic illustration of the sample measurement geometry is shown in Fig. 1. A Keithley-2400 source meter was employed for all the electrical measurements.

3. Results and discussion

Fig. 1(b) shows the specific heat plot at zero field between 2 and 300 K and the *R–T* plot between 50 and 300 K for the applied current of 0.01 mA. Specific heat data shows no major anomaly apart from the spin-glass transition as a minor hump at 44 K. Resistance data gives the impression of semiconductor-like behavior in the measured temperature range. The measurement was performed in pulse mode (during heating cycle) with 1 s pulse-off time to minimize JH. The surface temperature of the specimen is recorded simultaneously which is plotted against base temperature in inset. The linear dependence (slope ≈ 1) confirms that the sample temperature follows the base temperature. The sample resistance was too high to measure below 50 K. It is interesting to note that TSMO50 does not show any metal-insulator transition or charge ordering anomaly here in the measured temperature window unlikely in many other half doped manganites [1].

dc *I–V* measurements at different temperatures above 50 K are plotted in Fig. 2 for a maximum current of 1 mA. Each voltage measurement is made after stabilizing the current for 100 ms. The *I–V* curves are highly nonlinear and a large magnitude of NDR is discernible above a critical current, I_{cr}, at low temperatures. I_{cr} changes with base temperature. At 55 K, I_{cr} is 0.05 mA and shifts to higher values with increase in base temperature. It is clear that the *I–V* plot is not symmetric about its origin at low temperatures. The maximum voltage recorded is high in the first sweep direction as compared to the reverse current of same magnitude. At sufficiently high temperatures (above 200 K), the loop is symmetric (plots are not shown). Since the applied contact geometry does not resemble a well defined capacitor, charging (either in +ve or −ve current cycle) and discharging during polarity switching was ruled out. It is relevant to mention that the JH is independent of current direction. Since the resistance of the sample is high at low temperature, resistive heating and consequently, a fall in resistance. *A*-site disordered manganites are reported to exhibit low thermal conductivity where disorder limits free phonon propagation [17,18]. Due to poor thermal conductivity and low specific heat, sample fails to cool to the base temperature before entering the −ve quadrant. When the measurement with −ve current commences, it can be seen as if the sample experiences a higher temperature where the resistance is low and consequently, the maximum voltage will be less. This explains asymmetric hysteresis behavior.

To consolidate, and to estimate the increase of the sample temperature, we used the most accepted technique: by monitoring the changes in surface temperature. The sample temperature was sensed at each point during the *I–V* measurement (maximum sweep current was 1 mA) by employing a PT-100 sensor glued on the top surface. During the measurement, base temperature is found to be constant with time. The difference between base temperature (T_B) and monitored sample surface temperature (T_S) is termed as ΔT_{sur} and is plotted in inset of Fig. 2 against the sweep current. At a steady base temperature of 55 K, ΔT_{sur} is 11 K. As the measurement temperature increases, the quantum of increase in sample temperature is progressively reduced. JH is directly dependent on the applied current ($P = I^2R$). It is noted that the maximum ΔT_{sur} observed is not at the maximum current recorded. Since the PT 100 sensor has a finite response time, ΔT_{sur} lags behind the applied current.

If we compare the *I–V* plot and corresponding ΔT_{sur}, it is highly

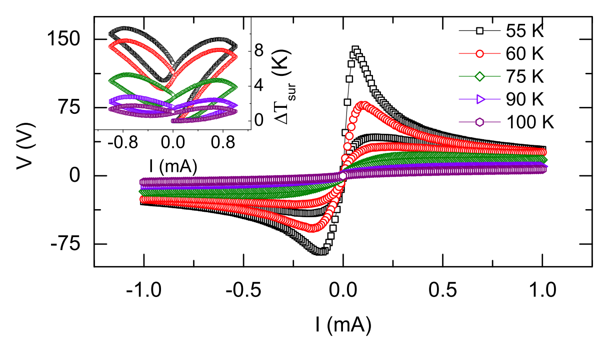

Fig. 2. Dc *I–V* measurement plots at different constant base temperatures. Change in sample surface temperature (ΔT_{sur}) is monitored simultaneously during the measurement and is presented in inset.

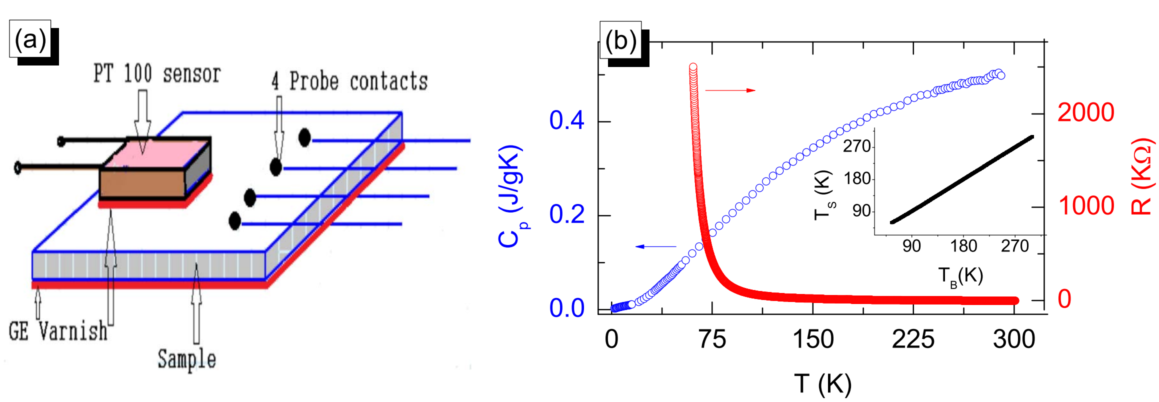

Fig. 1. (a) Schematic of sample measurement geometry. The sample is thermally anchored on the cold finger of CCR using GE/IMI-7031 varnish and the temperature of the base of the sample is measured using silicon diode sensors attached to the cold finger (not shown in figure). (b) Specific heat data in temperature range 3–300 K at zero field and the resistance-temperature measurement plot in 50–300 K range for 0.01 mA current. The inset shows the T_S vs T_B plot during the measurement.