Materials Parameter Extraction using Analytical Models in PCMO based RRAM

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Introduction: Manganite based bipolar RRAM are attractive for non-stochastic switching, area-dependent current scaling, fast switching and long endurance [1], forming-less operation [2]. Various mechanisms of switching have been proposed including Schottky barrier like interface resistance switching [3], SCLC and Metal – Insulator Mott-Transition [4]. Alternatively, trap based space-charge-limited-current (SCLC) has been used explain the IV characteristics qualitatively for a related materials system Ag/$La_{0.7}Ca_{0.3}MnO_3$/Pt [5]. An interfacial trap density with exponential energy distribution has been speculated without a quantitative verification of trap energy or position. To resolve this issue, we present a method of extracting trap density and verify the spatial and energy distribution using simple analytical expressions.

Device Fabrication and Characterization: A 50nm layer of $Pr_{0.7}Ca_{0.3}MnO$(PCMO) was deposited at room temperature on a substrate with bottom electrode of Pt (57nm)/Ti (9nm) deposited on SiO_2/Si substrate. It was then annealed at 650°C in N_2 for 120s (Fig. 1). Tungsten probe-tips were used as top electrode for facile characterization [6]. The IV characteristics (Fig. 2) show that the resistance of the High Resistance State (HRS) increases with increase in reset voltage (V_{reset}).

Current Transport Regimes and Models: The log-log plot (Fig. 3) of the IV characteristic shows 4 distinct regimes based on the exponent α of V i.e. $I \sim V^{\alpha}$ (i) Ohmic ($\alpha \sim 1$) (ii) Trap SCLC ($\alpha \sim 2$) (iii) Trap-filled Limit ($\alpha >> 2$) (iv) Trap – free SCLC ($\alpha \sim 2$). The band diagram (Fig. 4) on p-type PCMO device in the Ohmic region (very low bias almost equilibrium) is shown. A spatially uniform single energy (E_T) trap level is assumed (to be validated later). The spatially uniform trap level is filled in accordance to the Fermi level in a position dependent manner where it has a high trapped charge density near the interface which decays towards the bulk. The resistance of the Ohmic region depends upon the most resistive region where the valence band peaks and hole density is the lowest i.e. at ϕ_{max}. The Ohmic current density (Eq. 1) at a small fixed bias (0.04V) may be used to extract ϕ_{max} (Fig. 4). The relation between trap-free SCLC (Eq. 2) and trap SCLC (Eq. 3) are given by θ which is related to N_V, N_T and E_T-E_V(Eq. 4). Further, trap-free-limit voltage (V_{TFL}) is given (Eq. 5) by is extracted at an arbitrary fixed slope of α i.e. $\frac{d\alpha}{dlnV} \geq 20$ (Fig. 4).

Materials Parameter Extraction Methodology & Results: To extract materials parameters (Fig. 5), **first** the product of mobility(μ) & permittivity(ε) is extracted from Trap-Free SCLC (Eq. 2) [7]. For further analysis we assume $\mu\varepsilon$ product to be constant (~110) as they are material properties. We use relative permittivity of '30' for PCMO which is in the same order as that of experimentally determined value of relative permittivity (30~40) [8][9]. **Second**, N_{T_TFL} is extracted from V_{TFL} for various V_{reset} using (Eq. 5). N_{T-TFL} is linearly correlated with V_{reset} for HRS (Fig. 7(a)) while N_{T-TFL} is independent of V_{reset} in LRS. **Third**, θ is extracted from ratio of trap-SCLC vs. trap-free currents (Eq. 3). **Fourth**, assuming N_V and using N_T and θ earlier, we show that E_T-E_V remains constant by (Eq. 4) for various V_{reset} for a spatially uniform trap distribution (Fig. 6). **Fifth**, using μ, we extract ϕ_{max} from the Ohmic region by Eq.4, followed by the extraction of trap density from the Ohmic regime ($N_{T-Ohmic}$) using E_T-E_V (Eq. 6). Trap density densities extracted from the two regimes are perfectly correlated (slope=1.18, negligible offset and goodness of fit R^2=0.99) (Fig. 7(b)). The two methods are reasonably independent as N_{T-TFL} is obtained from electrostatics at high-bias trap-filled limit regime when all the traps are filled, while $N_{t-Ohmic}$ is obtained at low bias (near equilibrium) when most of the traps are not filled. This consistency of estimated N_T obtained between low and high bias regimes is indeed a strong validation of the method.

Validation of Spatial Uniformity of trap density: The slight polarity dependent asymmetry in the experimental IV (Fig. 8) indicates that the device is not exactly symmetric. The metric of asymmetry is chosen as the current ratio in trap-SCLC at a given voltage (Fig. 9(b)). Based on extracted PCMO materials parameters TCAD simulations are used to estimate the varying extents of asymmetry in trap profile (Fig. 9(a)) to current ratio asymmetry in trap-SCLC regime. A maximum experimentally obtained current asymmetry is 1.2:1. Thus, building on (i) the excellent consistency of N_T extraction from the two different regimes (based on the uniform spatial trap density assumption) and (ii) the TCAD results indicating an estimate of 2:1 trap distribution asymmetry to produce the observed current ratio, we speculate that the assumption of uniform spatial distribution of trap density is reasonably valid.

Conclusions: In this paper, we have present analytical models based extraction of materials parameters for PCMO based RRAM. Based on a trap-SCLC model, the energy and spatial distribution of trap-density is extracted. A single-level trap energy is estimated. The uniform trap density model provides consistent trap density estimated from low bias Ohmic regime as well as high-bias Trap-Filled Limit regime.

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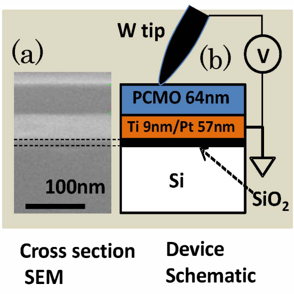


Fig. 1 (a) Cross SEM of Si/SiO$_2$/Ti/Pt/PCMO stack.
(b) Schematic of fabricated device. W probe is used as the top electrode

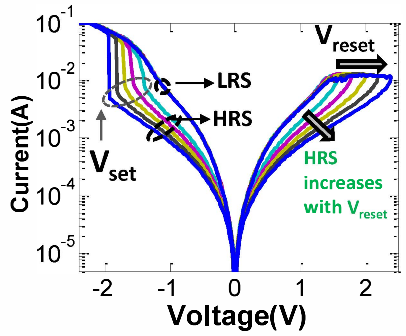


Fig. 2 IV characteristics for different maximum positive voltages (V_{reset}). The HRS changes with increase in V_{reset}.

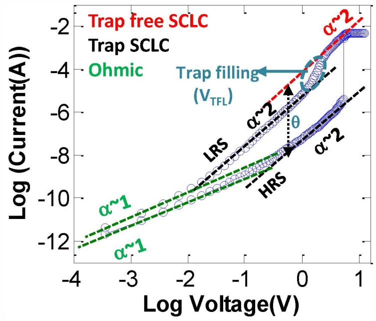
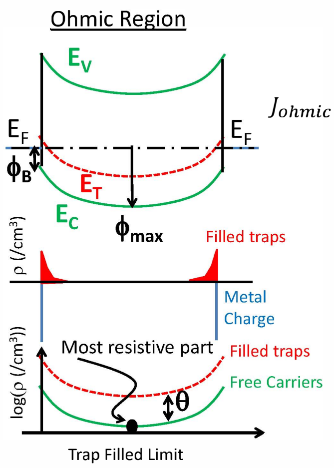


Fig. 3 IV characteristic showing 4 distinct regimes based on exponent, α, of V i.e. I~V$^{\alpha}$ (i) ohmic (α~1) (ii) Trap SCLC (α~2) (iii) Trap-filled Limit (α>>2) (v) Trap – free SCLC (α~2)



$$J_{ohmic} = \frac{qp_0\mu V}{L} = \frac{q\mu N_V}{L}\exp\left(-\frac{\varphi_{max}}{kT}\right)V \quad (1)$$

$$J_{trapfree} = \frac{9}{8}\frac{\mu\epsilon}{L^3}V^2 \quad (2)$$

$$J_{trap} = \frac{J_{trapfree}}{\theta} \quad (3)$$

$$\theta = \frac{N_V}{gN_T}\exp\left(-\frac{E_T - E_V}{kT}\right) \quad (4)$$

$$V_{TFL} = \frac{qN_TL^2}{2\epsilon g} \quad (5)$$

Poisson Equation

$$\frac{d^2\varphi}{dx^2} = -\frac{q^2}{\varepsilon}(\theta+1)N_T\exp\left(\frac{-\varphi + E_T - E_V}{kT}\right)$$

After integration,

$$\varphi_{max} - \varphi_B$$

$$= kT\ln\left(\sec^2\left(\frac{L}{2}\left(\frac{2q^2N_T}{kT\epsilon}(\theta+1)\exp\left(\frac{-\varphi_{max}+E_T-E_V}{kT}\right)\right)^{1/2}\right)\right)$$

Experimentally,

$$\frac{\varphi_{max}-\varphi_B}{kT} \gg 3 \rightarrow \exp\left(\frac{\varphi_{max}-\varphi_B}{kT}\right) \gg 1$$

$$\rightarrow \left(\frac{L}{2}\left(\frac{2q^2N_T}{kT\epsilon}(\theta+1)\exp\left(\frac{-\varphi_{max}+E_T-E_V}{kT}\right)\right)^{1/2}\right) \approx \frac{\pi}{2}$$

$$N_T = \left(\frac{\pi}{L}\right)^2 \cdot \frac{kT\epsilon}{2q^2(\theta+1)}\exp\left(-\frac{-\varphi_{max}+E_T-E_V}{kT}\right) \quad (6)$$

Fig 4 shows the band diagram of p-type PCMO in ohmic region with trap level at E_T. ϕ_{max} can be extracted from the ohmic current density. The equations giving the relation between trap-free SCLC (2) & trap-SCLC (3) and to extract V_{TFL} (3) are shown.

Fig 5. Shows the methodology to derive the relationship between N_T & □$_{max}$ from poisson's equation.

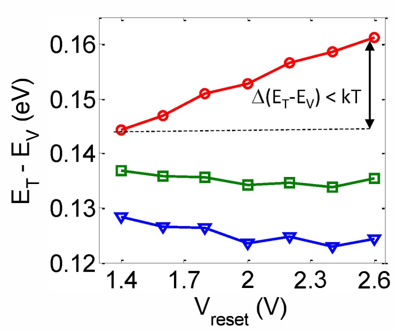


Fig. 6 shows that the variation in E_T-E_V is very less (<kT) w.r.t V_{reset}

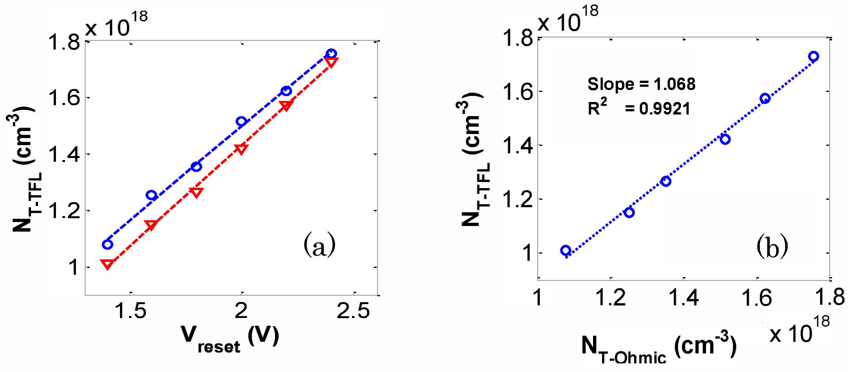


Fig. 7 (a) shows that $N_{T\text{-}Ohmic}$ & $N_{T\text{-}TFL}$ are linearly increasing with V_{reset}. (b) The linear correlation between $N_{T\text{-}Ohmic}$ & $N_{T\text{-}TFL}$ is shown.

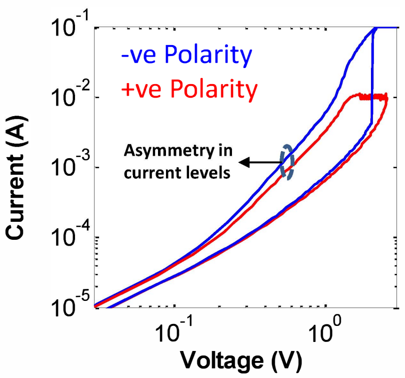


Fig. 8 shows the asymmetry in the currents in +ve & -ve polarity

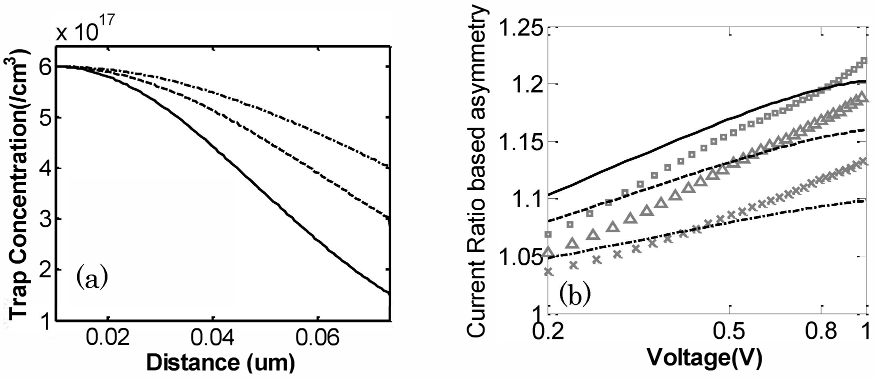


Fig. 9 Indication of low asymmetry (a) Shows various trap concentration profiles simulated (b) Corresponding simulated current ratios in opposite polarity of device at various Voltages and comparison to experimental measurements (indicated by symbols) with varying V_{reset}