



## Enhanced tunability of electrical and magnetic properties in (La,Sr)MnO<sub>3</sub> thin films via field-assisted oxygen vacancy modulation



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### ABSTRACT

We investigated the tunability of the transport and magnetic properties in 7.5 nm La<sub>0.7</sub>Sr<sub>0.3</sub>MnO<sub>3</sub> (LSMO) epitaxial films in a field effect geometry with the ferroelectric copolymer P(VDF-TrFE) as the gate insulator. Two different switching behaviors were observed upon application of gate voltages with either high or low magnitudes. The application of single voltage pulses of alternating polarity with an amplitude high enough to switch the remanent polarization of the ferroelectric copolymer led to a 15% change of the resistance of the LSMO channel at temperature 300 K (but less than 1% change at 20 K). A minimal shift of the peak in the resistance-temperature plot was observed, implying that the Curie temperature  $T_C$  of the manganite layer is not changed. Alternatively, the application of a chain of low voltage pulses was found to shift  $T_C$  by more than 16 K, and a change of the channel resistance by a 45% was obtained. We attribute this effect to the field-assisted injection and removal of oxygen vacancies in the LSMO layer, which can occur across the thickness of the oxide film. By controlling the oxygen migration, the low-field switching route offers a simple method for modulating the electric and magnetic properties of manganite films.

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### 1. Introduction

With the scaling down of non-volatile memory devices, power management has become one of the most pressing challenges for the semiconductor industry. For example, significant improvement was made to reduce the current density of spin-transfer torque magnetic random access memory (STT-MRAM) devices [1]. Besides using an electric current, the manipulation of the magnetic properties by an electric field can further reduce the power consumption. The manipulation of magnetism via an electric field has therefore attracted much attention [2–4]. Recent progress has demonstrated the successful control of saturation magnetization [5–7], Curie temperature [5,7–10], magnetic anisotropy [5,7,11] and exchange bias in magnetic thin films [5,12] or heterostructures [5,13,14].

Manipulating the magnetic properties in ferromagnets (FM) via an electric field can be classified into two approaches. The first approach relies on the magnetoelectric (ME) coupling between ferroelectric (FE) and magnetic order in a single phase multiferroic, which is promising for future multifunctional devices [2,12]. Unfortunately, only a few systems demonstrate the coexistence

of FE and FM [12,15]. Alternatively, artificial multiferroic heterostructures were also deployed to achieve the manipulation of magnetism via an electric field [16]. Such heterostructures consist of a FM that is gated with FE oxides. Based on the polarization reversal in the FE oxides, carriers in the FM film are attracted towards (or repelled from) the FM/FE interfaces. This electrostatic effect induces changes in the carrier concentration in the FM, accompanied by a change of the magnetic properties. However, FM metals have high carrier concentrations ( $10^{21}$ – $10^{22}$  cm<sup>-3</sup>), resulting in a very short electrostatic screening depth, and ultrathin FM layers are therefore required [16]. In general, for achieving high microstructural match quality between the FM and FE materials, epitaxial growth of FM and FE materials is required. For example, Pb<sub>x</sub>Zr<sub>1-x</sub>TiO<sub>3</sub> (PZT) and BaTiO<sub>3</sub> (BTO) are promising candidates due to their high FE polarization coefficients and compatibility with various FM oxides [4,17,18].

For high compatibility with different epitaxial FM oxide, FE polymers such as the copolymer of polyvinylidene fluoride with trifluoroethylene P(VDF-TrFE) have attracted much attention due to their unique properties. They are lead-free, they have a high flexibility and the highest dielectric constant ( $\kappa \sim 10$ ) among other FE polymer [19,20]. Stolichnov *et al.* used P(VDF-TrFE) as a FE layer

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