Supporting Information

Suppression of spin-orbit coupling effect by the ZnO layer of the $La_{0.7}Sr_{0.3}MnO_3/ZnO$ heterostructures grown on (001) oriented Si - restores the negative magnetoresistance

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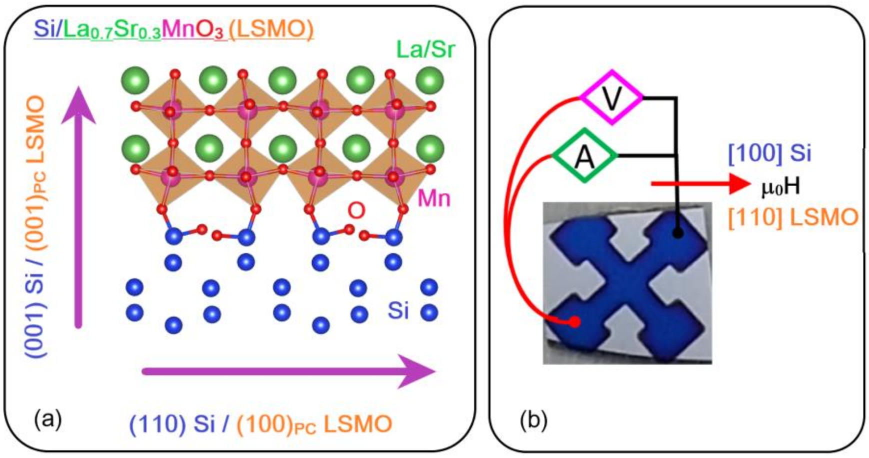

Figure S1. (a) Schematic for the growth orientation of $La_{0.7}Sr_{0.3}MnO_3$ on (001) oriented Si. (b) In-plane current and field orientations.

Figure S1a shows the growth orientation of pseudocubic (PC) LSMO on Si. The lattice constant of (100) of Si provides a large lattice mismatch with the lattice constant of (100) of LSMO for the epitaxial growth. Nevertheless, the lattice constant of (110) of Si leads to a better matching with the lattice constant (100) of LSMO, which provides the platform for the growth of LSMO on Si. The pseudocubic unit cell of LSMO is rotated by an angle of 45° around [001] of Si. Thus, the $(100)_{PC}$ of LSMO is parallel to (110) of Si, and $(110)_{PC}$ is parallel to (100) Si. The thin films and heterostructures were grown in the shape of a rectangular strip, such that the length of the strip is parallel to the (110) of Si (Fig. S1b).

The resistance of the LSMO thin films and LSMO-ZnO heterostructures was measured by the two probe method. The in-plane field-dependent resistance was measured by orienting the in-plane current to 45° with respect to the in-plane magnetic field using a setup comprised of an Advanced Research System made closed-cycle cryostat, a Lakeshore temperature controller, a Keithley picoammeter, a Keysight nanovoltmeter, and a copper coil solenoid electromagnet with an upper field limit of 1.3 kG [1] (Fig. S1b). In other words, the in-plane magnetic field is oriented along the (100) of Si, i.e., along the (110) of LSMO for the magnetotransport measurements of the LSMO films and heterostructures.

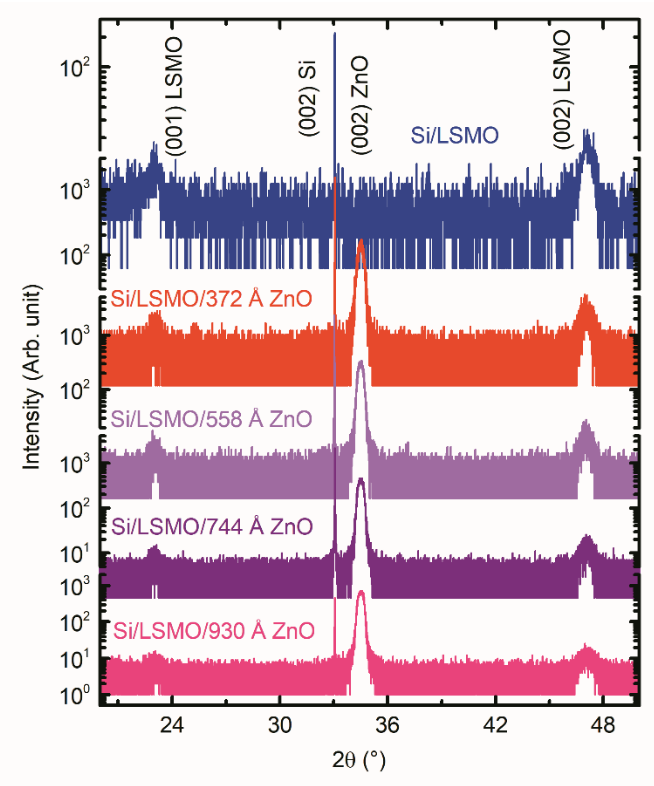

Figure S2. θ−2θ X-ray diffraction pattern of the (001)Si/120 Å $La_{0.7}Sr_{0.3}MnO_3$ and (001)Si/120 Å $La_{0.7}Sr_{0.3}MnO_3$/ZnO heterostructures with 372 Å, 558 Å, 744 Å, and 930 Å thick ZnO.

Figure S2 shows the θ−2θ X-ray diffraction pattern of the Si/120 Å $La_{0.7}Sr_{0.3}MnO_3$ and Si/120 Å $La_{0.7}Sr_{0.3}MnO_3$/ZnO heterostructures with 372 Å, 558 Å, 744 Å, and 930 Å thick ZnO. It is cleared that the LSMO and ZnO exhibit only $(00l)$ orientations. The LSMO peak occurs at the same 2θ value in the θ−2θ X-ray diffraction patterns of Si/LSMO and Si/LSMO/ZnO heterostructures for different ZnO thicknesses. Similarly, there is no significant shift in the ZnO peak, however, the peak intensity increases with an increase in ZnO thickness. The pseudocubic out-of-plane lattice constant "c" of LSMO suffers −0.28 % strain, while the strain in the out-of-plane lattice constant of wurtzite ZnO is negligible (0.08 %).

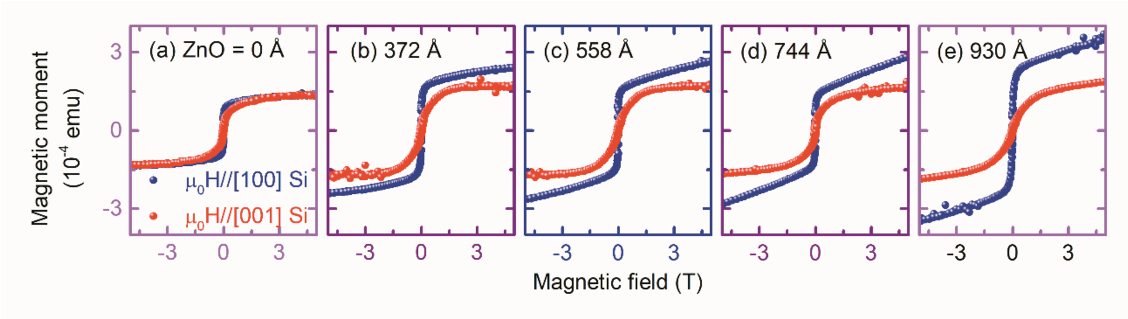

Figure S3. Zero-field-cooled field dependent magnetic moment of (a) (001)Si/ $La_{0.7}Sr_{0.3}MnO_3$ and (001)Si/$La_{0.7}Sr_{0.3}MnO_3$/ZnO with (b) 372 Å, (c) 558 Å, (d) 744 Å, and (e) 930 Å thick ZnO measured at 10 K with field oriented along [100] and [001] of Si.

Figure S3 displays the field-dependent magnetic moment M(H) of Si/LSMO film, and Si/LSMO/ZnO heterostructures with different ZnO thickness at 10 K. The M(H) was measured at 10 K with the magnetic field oriented along [100] and [001] of Si. All M(H) exhibit hysteretic behavior and possess magnetic anisotropy. It is clear from Fig. S3a that the [001] orientation of the magnetic field is the hard axis of LSMO. The M(H) of Si/LSMO/ZnO heterostructures does not show any saturation behavior even at $\pm 7\ T$, indicating the paramagnetic behavior of ZnO, and the paramagnetic volume increases with ZnO thickness (Fig. S3b-e). However, the paramagnetic contribution in the M(H) of Si/LSMO/ZnO heterostructures is negligible along [001].

Figure S4 shows the field dependence of in-plane magnetoresistance MR(H) of Si/LSMO film and Si/LSMO/ZnO heterostructures with different ZnO thicknesses at 10 K. The magnetic field is oriented at an angle of 45° with applied current, as shown in Fig. S1b. The Si/LSMO shows the maximum positive MR of ~11 % due to charge transfer driven strong localized antiferromagnetic coupling at the Si-LSMO interface (Fig. S4a). The growth of ZnO on the top of LSMO suppressed the positive MR (Fig. S4b-e). The detailed description and analysis of in-plane MR(H) are presented in our previous report. [1]

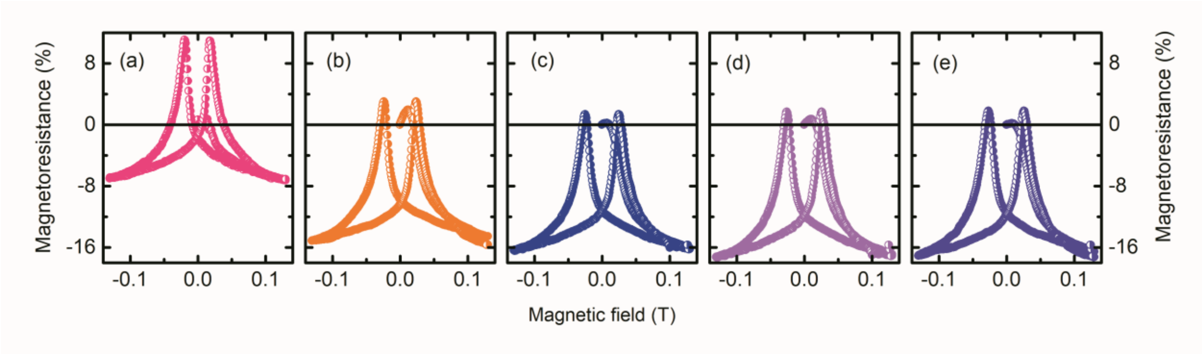

Figure S4. Field dependent in-plane magnetoresistance at 10 K of the (a) (001)Si/120 Å $La_{0.7}Sr_{0.3}$ MnO_3 and (001)Si/120 Å $La_{0.7}Sr_{0.3}MnO_3$/ZnO with (b) 372 Å, (c) 558 Å, (d) 744 Å, and (e) 930 Å thick ZnO.

References

1. B. Das and P. Padhan, *Appl. Phys. Lett.*, 2019, **115**, 222401.