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Mg-INDUCED ENHANCEMENT OF MEMRISTIVE SWITCHING IN SnO_2 THIN FILMS

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Magnesium-doped tin oxide (SnO_2:Mg) thin films have attracted considerable attention as promising materials for next-generation non-volatile memory devices due to their stable resistive switching behavior and simple fabrication processes. In this work, SnO_2 thin films were fabricated by ultrasonic spray pyrolysis using a precursor solution containing 20 mol.% Mg and systematically investigated to evaluate their memristive switching characteristics, electrical performance, and conduction behavior. Structural analysis confirmed the formation of uniform polycrystalline thin films with a crystallite size of approximately 30 nm, while energy-dispersive X-ray spectroscopy (EDS) revealed an actual Mg content of approximately 5 at.%, indicating partial incorporation of Mg into the SnO_2 lattice. Electrical measurements demonstrated reproducible bipolar resistive switching with an ON/OFF resistance ratio of approximately 10^3 and stable switching behavior over multiple cycles with low voltage variation (±5%) compared to previously reported undoped SnO_2 films. The observed improvement in memristive performance is attributed to Mg-induced modifications of defect states and charge-transport pathways within the oxide matrix. Conduction analysis indicates a transition from ohmic behavior at low bias to space-charge-limited conduction (SCLC) at higher voltages, consistent with a quadratic current–voltage relationship ($I \propto V^2$). These results demonstrate that Mg incorporation is an effective defect-engineering strategy for tuning the electrical properties of SnO_2 thin films and improving their suitability for reliable memristor and non-volatile memory applications. This approach provides a simple and scalable route for engineering oxide-based memristive devices.

Keywords: *SnO_2; Mg doping; Memristor; Resistive switching; Non-volatile memory*
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INTRODUCTION

Resistive switching phenomena in metal–oxide thin films have attracted significant attention due to their strong potential for application in next-generation non-volatile memory and neuromorphic computing systems [1–3]. Among oxide materials, tin oxide (SnO_2) is a promising candidate due to its wide band gap, good chemical stability, low fabrication cost, and compatibility with conventional semiconductor technologies [4–6]. However, the practical implementation of SnO_2-based memristive devices is still limited by issues related to switching stability, ON/OFF resistance ratio, and variability of electrical characteristics. Therefore, modifying the electrical and structural properties of SnO_2 through controlled doping has become an important research direction [7–12].

Magnesium (Mg) incorporation into SnO_2 is expected to influence charge-transport behavior, defect distribution, and carrier concentration within the oxide matrix, thereby directly affecting resistive-switching performance. Previous studies on doped metal-oxide memristors have demonstrated that appropriate dopant selection can enhance switching uniformity, reduce operating voltage, and improve endurance characteristics. However, most reported studies have focused on undoped or transition-metal-doped SnO_2 systems, while systematic investigations of Mg-doped SnO_2 thin films, particularly regarding memristive switching mechanisms and conduction behavior, remain limited [13–14].

In this work, we demonstrate that Mg doping acts as an effective defect-engineering approach in SnO_2 thin films, enabling modulation of oxygen vacancy distribution and stabilization of conductive filament formation. As a result, the fabricated devices exhibit improved switching reproducibility and an enhanced ON/OFF resistance ratio compared to previously reported undoped SnO_2 systems. The films were prepared using the ultrasonic spray pyrolysis technique and systematically investigated in terms of their structural, morphological, and electrical properties. Special attention was given to switching reproducibility, the resistance ratio, and the dominant charge transport mechanisms. The results provide new insight into Mg-induced defect states and their role in controlling charge transport and filament dynamics, highlighting a promising pathway to improve the performance and reliability of SnO_2-based memristive devices for non-volatile memory applications.

METHODS

Mg-doped SnO_2 (SnO_2:Mg) thin films were fabricated using the ultrasonic spray pyrolysis (USP) technique due to its cost-effectiveness, simplicity, and suitability for large-area oxide thin-film deposition. The Mg concentration in the

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precursor solution was fixed at 20 mol.% relative to the Sn precursor. The schematic configuration of the USP deposition system is shown in Figure 1, in which the precursor aerosol generated by an ultrasonic nebulizer is transported by a carrier gas into a heated quartz reaction chamber to form a thin film on the substrate.

In this study, p-type silicon (p-Si) substrates were employed as the bottom electrode and supporting platform. Prior to deposition, the substrates were sequentially cleaned in deionized water, ethanol, and acetone, followed by a final rinse in deionized water to remove organic and inorganic contaminants and ensure uniform film adhesion. The cleaned substrates were dried under ambient conditions and subsequently dried using nitrogen gas to eliminate residual moisture.

The fabricated memristor device consists of a single-layer SnO_2 thin film prepared using a precursor solution containing 20 mol.% Mg, deposited on a p-Si substrate in a vertical metal–insulator–semiconductor configuration. Circular silver (Ag) top electrodes were formed using conductive silver paste, while the p-Si substrate served as the bottom electrode. This sandwich-type geometry enables electric-field-driven charge transport through the SnO_2:Mg layer, which is essential for investigating memristive resistive switching behavior.

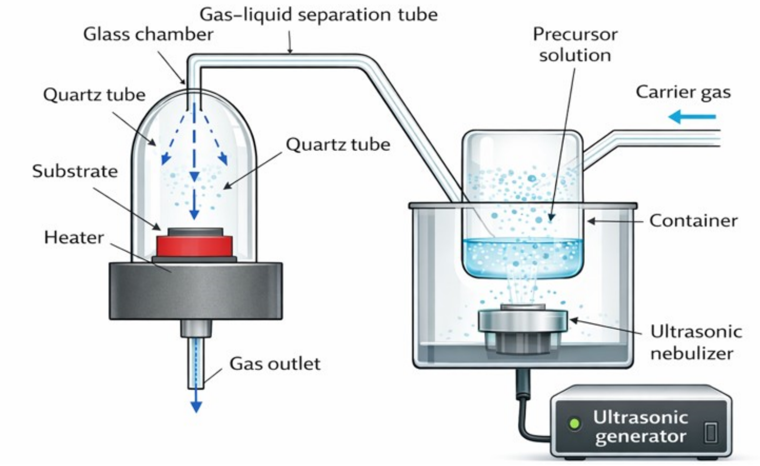

Figure 1. Schematic diagram of the ultrasonic spray pyrolysis system used for the deposition of SnO_2 thin films prepared from a precursor solution containing 20 mol.% Mg

The precursor solution was prepared by dissolving stannous chloride dihydrate ($SnCl_2 \cdot 2H_2O$) in double-distilled water, followed by the addition of a magnesium salt corresponding to 20 mol.% Mg doping. The solution was magnetically stirred at room temperature until complete homogenization was achieved. As illustrated in Figure 1, the precursor solution was atomized using a 2.5 MHz ultrasonic transducer and transported toward the heated substrate by an oxygen carrier gas.

Film deposition was carried out at a substrate temperature of 450 °C maintained by a temperature-controlled hotplate. After deposition, the films were annealed in ambient air at the same temperature to improve crystallinity, reduce structural disorder, and stabilize the electrical properties of the SnO_2:Mg layer. Silver top electrodes were subsequently formed for electrical characterization.

Electrical measurements of the memristor devices were performed at room temperature using a Keithley 2460 SourceMeter. A voltage sweeps sequence of $0 \rightarrow +5\ V \rightarrow 0 \rightarrow -5\ V \rightarrow 0$ was applied to record the current–voltage (I-V) characteristics. The pinched hysteresis loop confirmed the memristive resistive-switching behavior of the fabricated SnO_2:Mg thin-film structures.

RESULTS AND DISCUSSION

a. Optical properties

The optical properties of the Mg-doped SnO_2 thin film were analyzed using the Tauc method derived from diffuse reflectance measurements, and the corresponding Tauc plot is shown in Figure 2. The optical bandgap energy was determined by plotting the squared Kubelka–Munk function, $(F(R)h\nu)^2$, as a function of photon energy ($h\nu$) and extrapolating the linear region of the absorption edge to the energy axis.

As illustrated in Figure 2, the Tauc plot indicates a direct optical transition with an estimated bandgap value of approximately 3.75 eV for the SnO_2:Mg thin film. This value is slightly lower than that of undoped SnO_2, which is typically reported in the range of 3.6–4.0 eV, suggesting that Mg incorporation introduces localized defect states and band tailing near the conduction band. Such bandgap modification is commonly associated with oxygen-vacancy-related states and lattice distortion induced by substitutional doping.

The presence of defect-mediated sub-bandgap states is particularly relevant to memristive behavior, as these states can act as carrier-trapping centers and facilitate charge transport under an external electric field. Consequently, the bandgap narrowing and defect-related optical features observed in Figure 2 support enhanced resistive-switching performance and the formation of conductive filaments in the SnO_2:Mg memristor structure.

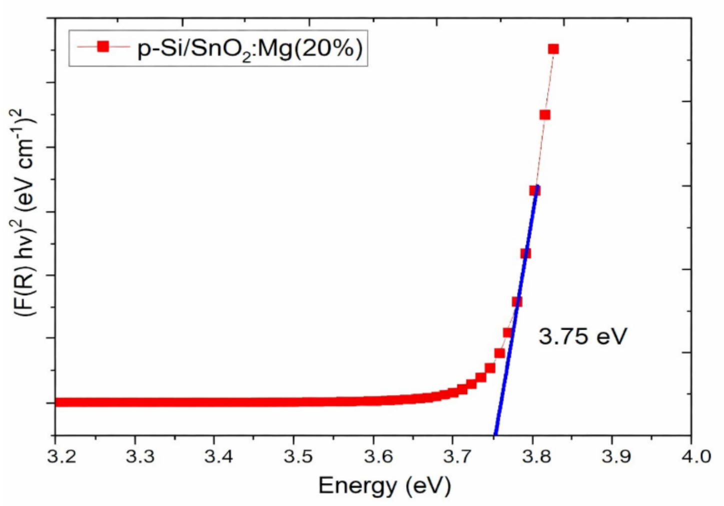

Figure 2. Tauc plot of the Mg-doped SnO_2 thin film showing a direct optical bandgap of approximately 3.75 eV

b. Structural properties from X-ray diffraction analysis

The crystal structure and phase composition of the Mg-doped SnO_2 thin films were analyzed by X-ray diffraction (XRD), and the corresponding diffraction pattern is presented in Figure 3. The pattern confirms that the deposited films retain the tetragonal rutile crystal structure characteristic of SnO_2, indicating that magnesium incorporation does not alter the fundamental crystallographic phase of the host material. The main diffraction peaks corresponding to the (110), (101), (200), and (211) crystallographic planes observed in Figure 3 are consistent with standard reference data for crystalline SnO_2, demonstrating the successful formation of well-crystallized oxide thin films.

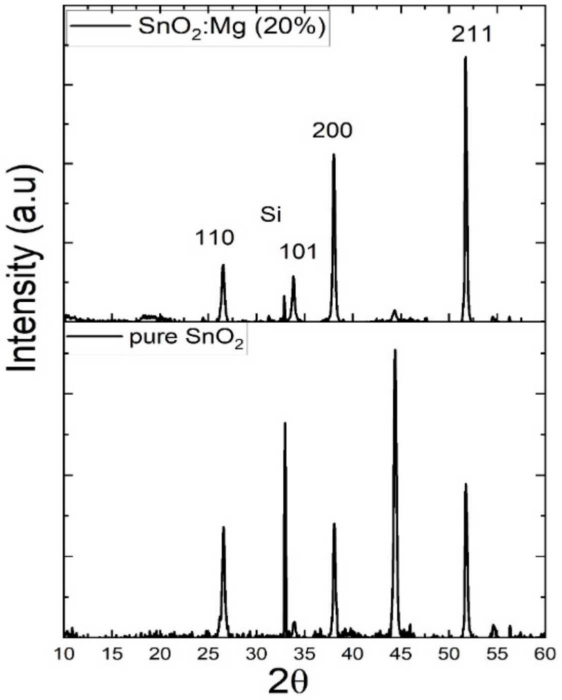

Figure 3. XRD pattern of the Mg-doped SnO_2 thin film showing the tetragonal rutile phase with dominant (110), (101), (200), and (211) reflections and no detectable secondary phases.

No additional reflections associated with MgO or other secondary impurity phases are detected within the measurement range shown in Figure 3. This absence of secondary phases suggests that Mg ions are incorporated substitutionally into the SnO_2 lattice rather than forming segregated compounds. Such substitutional incorporation is expected to induce local lattice distortion and modify the defect distribution within the oxide matrix.

In addition, energy-dispersive X-ray spectroscopy (EDS) analysis confirmed the presence of Mg in the deposited films, with an average concentration of approximately 5 at.%. This value is lower than the nominal precursor concentration (20 mol.%), indicating partial incorporation of Mg into the SnO_2 lattice during the ultrasonic spray pyrolysis process. The discrepancy between the precursor composition and the measured film composition can be attributed to incomplete incorporation efficiency and possible re-evaporation of Mg species during deposition.

As also evident from the peak profiles in Figure 3, a slight broadening of the diffraction peaks compared with undoped SnO_2 indicates a decrease in crystallite size together with an increase in microstrain and defect concentration caused by Mg incorporation. These structural changes are particularly important for memristive behavior, since they enhance the generation and migration of oxygen vacancies that serve as the dominant charge transport centers in oxide-based resistive switching devices. The increased density and mobility of oxygen vacancies facilitate conductive filament formation under an applied electric field, thereby improving switching stability and reproducibility in SnO_2:Mg memristors.

The structural parameters extracted from the XRD data are summarized in Table 1. The average crystallite size, calculated using the Scherrer equation, was found to be approximately 30 nm. Furthermore, the estimated microstrain ($\varepsilon \approx 1.2\times10^{-3}$) and dislocation density ($\delta \approx 1.2\times10^{15}$ m^{-2}) confirm an increased defect density induced by Mg incorporation. These microstructural features are directly correlated with enhanced oxygen vacancy mobility and improved memristive switching performance.

Table 1. Structural parameters of Mg-doped SnO_2 thin films derived from XRD analysis

(hkl)	2θ (deg)	d-spacing (Å)	Relative Intensity	FWHM (rad)	Crystallite Size (nm)
(110)	26.6°	3.35	Medium	0.005	30
(101)	33.9°	2.64	Low–Medium	0.006	27
(200)	37.9°	2.37	High	0.0055	28
(211)	51.8°	1.76	Very High	0.0048	31

c. Electrical properties and memristive switching behavior

The electrical characteristics of the Mg-doped SnO_2 thin film device were investigated using current–voltage (I–V) measurements in the voltage range from approximately −5 V to +5 V. As shown in Figure 4, the I–V curve exhibits a well-defined pinched hysteresis loop passing through the origin, which is a characteristic signature of memristive behavior. The device demonstrates bipolar resistive switching between a high-resistance state (HRS) and a low-resistance state (LRS), with an ON/OFF resistance ratio of approximately 10^3, confirming the formation of a stable resistive memory effect in the SnO_2:Mg thin film.

At low applied voltages, the current varies linearly with voltage, indicating ohmic conduction dominated by thermally generated free carriers. As the voltage increases, the current transitions to a nonlinear regime associated with space-charge-limited conduction (SCLC), suggesting trap-controlled charge transport within the oxide layer. The SCLC region is confirmed by the quadratic dependence of current on voltage ($I \propto V^2$). This transition from ohmic to SCLC conduction is consistent with defect-mediated transport mechanisms commonly observed in oxide-based memristive systems.

The asymmetry observed between the positive and negative voltage sweeps in Figure 4 indicates that the resistive switching process is governed by electric-field-driven migration of oxygen vacancies and the formation and rupture of conductive filaments across the SnO_2:Mg layer. The SET process occurs at approximately +3 V, where vacancy accumulation leads to filament formation and transition to the LRS, while the RESET process occurs near −3 V, corresponding to partial filament rupture and recovery of the HRS. The variation in switching voltages remains within ±8%, indicating good cycle-to-cycle uniformity and device stability.

Compared to previously reported undoped SnO_2 devices, the Mg-doped films exhibit improved switching reproducibility and reduced variability, which can be attributed to the more controlled distribution of oxygen-vacancy-related defect states induced by Mg incorporation.

The stability and reproducibility of the switching behavior were further evaluated through repeated voltage cycling, as presented in Figure 5. The device demonstrates stable resistive switching over more than 50 consecutive cycles, with only minor variation in the I–V characteristics while maintaining a consistent hysteresis window. The variation in SET and RESET voltages remains within ±5%, indicating good cycle-to-cycle uniformity and stable filament formation dynamics.

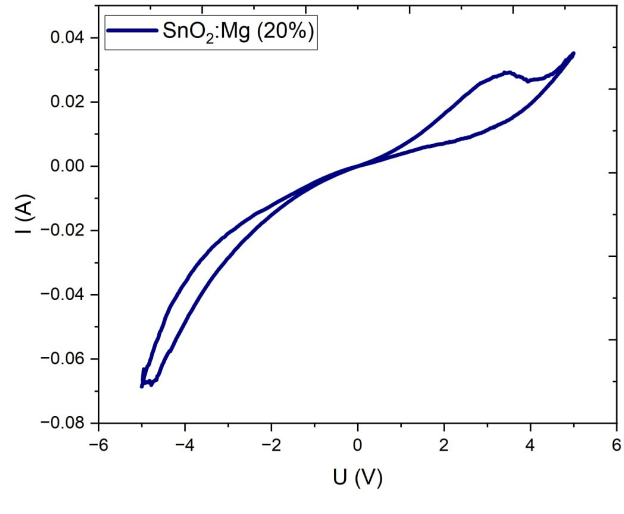

Figure 4. Current–voltage characteristics of the Mg-doped SnO_2 thin film showing bipolar memristive switching behavior

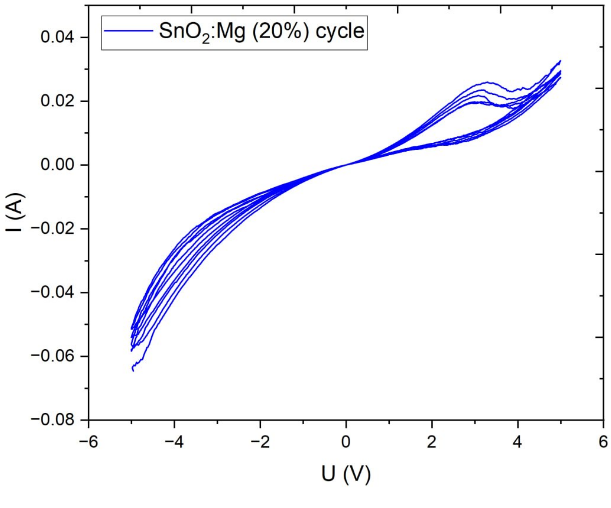

Figure 5. Multi-cycle I–V curves of the Mg-doped SnO_2 device demonstrating reproducible switching and stable hysteresis

Such endurance characteristics confirm the reliability of Mg-doped SnO_2 thin films for non-volatile memory and neuromorphic device applications.

Overall, the electrical analysis demonstrates that Mg incorporation enhances defect-mediated charge transport and stabilizes filamentary switching, resulting in an ON/OFF resistance ratio of approximately 10^3 and improved switching reproducibility compared to previously reported undoped SnO_2 thin films.

CONCLUSIONS

In this work, magnesium-doped SnO_2 thin films were prepared using a precursor solution containing 20 mol.% Mg were successfully fabricated by the ultrasonic spray pyrolysis technique and systematically investigated in terms of their structural and electrical properties. The results confirm that Mg incorporation preserves the tetragonal rutile crystal structure of SnO_2 without the formation of secondary impurity phases, while inducing lattice distortion, reduced crystallite size (≈ 30 nm), and increased defect density. These structural modifications enhance oxygen-vacancy migration and facilitate the formation of conductive filaments within the oxide layer.

Electrical measurements reveal stable bipolar resistive switching with a pronounced pinched hysteresis loop and an ON/OFF resistance ratio of approximately 10^3. The device exhibits reproducible switching behavior over multiple voltage cycles with low variation in switching voltages (±5%). The conduction mechanism transitions from ohmic transport at low bias to space-charge-limited current (SCLC) at higher voltages, consistent with trap-controlled charge transport ($I \propto V^2$). The switching process is governed by an oxygen-vacancy-driven filamentary conduction mechanism, where Mg doping plays a crucial role in stabilizing filament formation and reducing switching variability.

Compared with previously reported undoped SnO_2 systems, the Mg-doped films demonstrate improved switching reproducibility and enhanced resistance ratio, highlighting the effectiveness of Mg as a defect-engineering dopant. Overall, the results provide new insight into defect-controlled resistive switching and confirm that Mg incorporation is a promising strategy for improving the performance and reliability of SnO_2-based memristive devices.

These findings indicate that SnO_2:Mg thin films fabricated by ultrasonic spray pyrolysis represent a promising material platform for next-generation non-volatile memory and neuromorphic applications. Future work will focus on systematically varying Mg concentration to further optimize switching characteristics and better understand the underlying physical mechanisms.

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Mg-ІНДУКОВАНЕ ПОСИЛЕННЯ МЕМРИСТИВНОГО ПЕРЕМИКАННЯ В ТОНКИХ ПЛІВКАХ SnO_2

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Тонкі плівки оксиду олова (SnO_2:Mg), легованого магнієм, привернули значну увагу як перспективні матеріали для енергонезалежних пристроїв пам'яті наступного покоління завдяки своїй стабільній резистивній поведінці перемикання та простим процесам виготовлення. У цій роботі тонкі плівки SnO_2 були виготовлені методом ультразвукового розпилювального піролізу з використанням розчину-попередника, що містить 20 мол.% Mg, та систематично досліджені для оцінки їхніх характеристик мемристивного перемикання, електричних характеристик та поведінки провідності. Структурний аналіз підтвердив утворення однорідних полікристалічних тонких плівок з розміром кристалітів приблизно 30 нм, тоді як енергодисперсійна рентгенівська спектроскопія (EDS) виявила фактичний вміст Mg приблизно 5 ат.%, що вказує на часткове включення Mg у решітку SnO_2. Електричні вимірювання продемонстрували відтворюване біполярне резистивне перемикання зі співвідношенням опору вмикання/вимикання приблизно 10^3 та стабільну поведінку перемикання протягом кількох циклів з низькими змінами напруги (±5%) порівняно з раніше зареєстрованими нелегованими плівками SnO_2. Спостережуване покращення мемристивної продуктивності пояснюється модифікаціями дефектних станів та шляхів переносу заряду, індукованими Mg, в оксидній матриці. Аналіз провідності вказує на перехід від омічної поведінки при низькому зміщенні до провідності, обмеженої просторовим зарядом (SCLC), при вищих напругах, що узгоджується з квадратичною залежністю струм-ампера ($I \propto V^2$). Ці результати демонструють, що впровадження Mg є ефективною стратегією дефектної інженерії для налаштування електричних властивостей тонких плівок SnO_2 та підвищення їхньої придатності для надійних мемристорів і енергонезалежної пам'яті. Цей підхід забезпечує простий та масштабований шлях для розробки мемристивних пристроїв на основі оксиду.

Ключові слова: *SnO_2; легування Mg; мемристор; резистивне перемикання; енергонезалежна пам'ять*