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TUNABLE NEGATIVE DIFFERENTIAL RESISTANCE IN SnO_2:Co MEMRISTORS ON p-Si

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This study investigates the negative differential resistance (NDR) phenomenon in cobalt-doped tin dioxide (SnO_2:Co) memristors fabricated on p-type silicon substrates. Using ultrasonic spray pyrolysis (USP), crystalline SnO_2:Co thin films were deposited on p-Si substrates with a thin native SiO_2 layer. The resulting memristor devices exhibit reproducible bipolar resistive switching between high-resistance (HRS) and low-resistance states (LRS). Key findings include the observation of a distinct NDR region in the current-voltage (I-V) characteristics, specifically in the positive voltage range from approximately +3V to +4V. Within this NDR region, current decreases despite increasing voltage, a characteristic hallmark of this effect. This behavior is attributed to the charge trapping and redistribution within the Co:SnO_2 material. The consistent and reproducible nature of the observed NDR effect suggests the potential of SnO_2:Co memristors for applications in advanced memory and switching technologies. This work contributes to the understanding of resistive switching mechanisms in Co-doped SnO_2 thin films, which are promising materials for next-generation memory devices.
Keywords: *SnO_2 doped by cobalt; Memristor; Negative differential resistance switching; USP*
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INTRODUCTION

Resistive switching phenomenon with different performance characteristics have been reported in various materials, including solid electrolyte [1], perovskites [2], organics [3] and binary transition metal oxides [4]. Among those materials, the metal oxides represent with many advantages of low cost, facile sample preparation. As one of the most studied wide bandgap semiconductors, ZnO thin films [5], Mg-ZnO films [6], CuO [7] and nanorods [8] as well as Mn-ZnO films [9] have been reported to shown stable resistive switching behavior.

However, study of the resistive switching property in cobalt-doped SnO_2 is few. It is well known that Co-doped SnO_2 is diluted magnetic semiconductor and is would be of great interesting to realized the resistive switching property. In this work, we demonstrate that 1%-5% cobalt-doped SnO_2 films-based metal-insulator-metal (MIM) structure exhibit reproducible bipolar resistive switching behavior. Building upon this foundation, our study delves deeper into the specific mechanisms and characteristics of resistive switching in cobalt-doped tin dioxide. While prior research has explored the potential of various materials for resistive memory applications, the unique combination of magnetic doping and semiconductor properties in Co-doped SnO_2 presents an opportunity to engineer novel functionalities beyond conventional resistive switching. This includes the potential for achieving tunable switching parameters, enhanced device performance, and even the integration of spin-based functionalities into memristive devices.

A critical aspect of this work is the exploration of the negative differential resistance (NDR) phenomenon exhibited by our Co-doped SnO_2 memristors. NDR, characterized by a decrease in current with an increase in voltage, holds significant promise for applications in low-power logic circuits, oscillators, and neuromorphic computing architectures. This study aims to precisely characterize the NDR behavior, identify the underlying physical processes driving it, and assess its impact on the overall performance of the fabricated devices. We aim to demonstrate that by carefully controlling the doping levels and material processing conditions, the NDR effect can be reliably harnessed for practical applications.

The insights gained from this investigation not only contribute to a better understanding of the fundamental properties of Co-doped SnO_2 but also pave the way for the development of innovative memory and switching devices with improved efficiency and novel functionalities. Our approach aims to bridge the gap between theoretical potential and practical realization, positioning Co-doped SnO_2 as a viable candidate for next-generation electronics.

METHODS

The cobalt doped SnO_2 films were deposited on heavily doped p-type silicon (100) substrates by ultrasonic spray pyrolysis method at ambient atmosphere, as described in details in [8]. All chemical reagents utilized in the present study were of analytical grade and used without further purification. The aqueous solution of tin acetate (0.5 mol/l) and cobalt acetate (0.005 mol/l and 0.001 mol/l) were used as the sources of Sn and Co, respectively. The substrate temperature was set at 450°C and the thickness of SnO_2:Co film was about 200 nm. In order to measure the electrical properties of the

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SnO_2:Co films, Ag top electrodes of 220 µm in diameter with 100nm thickness were thermally evaporated with a metal shadow mask. The current-voltage (I-V) characteristics of Ag/SnO_2:Co/SiO_2/p-type Si structure were measured by a Keithley 2460 source-measure unit. During the measurement in voltage sweeping mode, the positive bias was defined by the current flowing from the top electrode to bottom electrode, and the negative bias was defined by the opposite direction. To ensure the reliability and reproducibility of our measurements, several steps were taken to standardize the electrical characterization process. The Keithley 2460 source-measure unit was configured to perform voltage sweeps with a step size of 0.05V, while the compliance current limit was set at 10 mA to prevent any irreversible damage to the devices. Prior to each measurement, the system was calibrated to minimize any systematic errors, and the contact resistance between the probe tips and top electrodes was carefully verified. The measurements were conducted at room temperature under ambient atmospheric conditions, without any external illumination, unless stated otherwise. For each sample, I-V curves were recorded at multiple locations to assess the device-to-device variability. Furthermore, for detailed analysis of the switching behavior, including the endurance and retention characteristics of the devices, we performed repeated I-V cycling measurements and monitored the resistance state over time. Endurance tests were conducted by performing multiple voltage sweeps between the set and reset voltages, while retention tests were carried out by monitoring the change in the resistance at a fixed bias voltage. In order to establish the statistical significance of our results, we analyzed data from multiple devices and multiple measurement runs. The data processing and curve plotting were performed using OriginPro software, which allowed for precise determination of device parameters, such as switching thresholds and the negative differential resistance region. A schematic illustration of the device structure is included for clarity (Fig. 1).

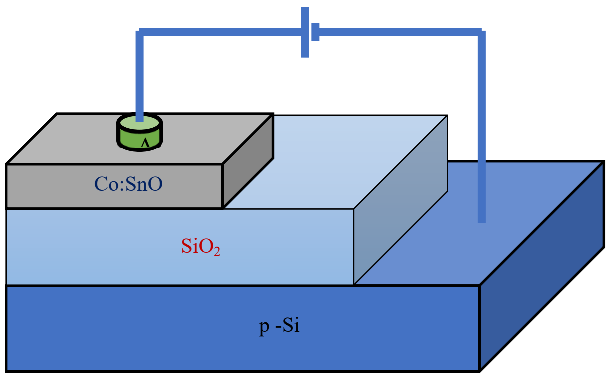

Figure 1. Schematic diagram of the Ag/Co:SnO_2/SiO_2/p-Si-based memristor structure. The top layer consists of a silver (Ag) contact, followed by a cobalt-doped tin oxide (Co:SnO_2) layer. This layer is deposited on a silicon dioxide (SiO_2) insulating layer, which is built on a p-type silicon (p-Si) substrate. The electrical properties of the memristor are studied by applying an external voltage

RESULTS

The current-voltage characteristic of a tin oxide material doped with 1% cobalt, typical of an RRAM device with an Ag/SnO2:Co/SiO2/p structure at room temperature (RT), is shown in Figure 2. Starting from 0V, as the voltage is increased in the positive direction, the current begins to increase non-linearly. It reaches a peak current value around 5V before dropping slightly as the voltage starts to decrease. This forms a clearly visible clockwise loop. The shape suggests that the device is switching between different resistance states, a common characteristic in memristive devices. As the voltage is swept negatively, a similar pattern is seen. The material initially has very low current, almost zero, until the voltage goes more negative than -3 V. At this point, the current suddenly increases sharply negatively. This abrupt change in current indicates that the device exhibits bipolar resistive switching behavior.

The Fig.3 shows the current-voltage characteristic of a tin oxide material that has been doped with 5% cobalt. The presence of a negative differential resistance (NDR) region is clearly evident in the graph depicted in the figure. In the positive voltage region, a portion of the graph shows a decrease in current with an increase in voltage (between +3V and +4V). This phenomenon is recognized as the Negative Differential Resistance (NDR) effect. Within this region, the material's resistance increases, leading to a temporary reduction in the current. An increase in voltage causes a change in the internal electric field of the material, thereby obstructing charge movement and consequently reducing the current. When the current decreases, the resistance of the material increases. This results in a temporary reduction of the material's ability to conduct electrical current. The current-voltage (I-V) graph illustrates how the current's direction and magnitude vary with both positive and negative applied voltages. The negative differential resistance (NDR) effect is seen solely within the positive voltage range. Following the negative differential resistance (NDR) region, the current rises again, suggesting that the device is capable of providing stable measurements. The consistent nature of the changes in the graph indicates the reproducibility of this characteristic. Beyond the qualitative observations described above, a detailed quantitative analysis was performed on the I-V characteristics presented in Figures 2 and 3. In the 1% Co-doped sample (Figure 2), while a hysteretic behavior indicative of resistive switching is apparent, the NDR effect is not prominent. The switching threshold voltages were measured to be approximately ±2.5V for this device. However, a notable and robust NDR phenomenon is observed in the 5% Co-doped sample (Figure 3), with the NDR region occurring between approximately +3V and +4V, as previously mentioned. The peak current before the onset of NDR was recorded to be around 15 mA, and a clear decrease in current is observed following the NDR region, eventually returning to higher current values upon further increase in voltage.

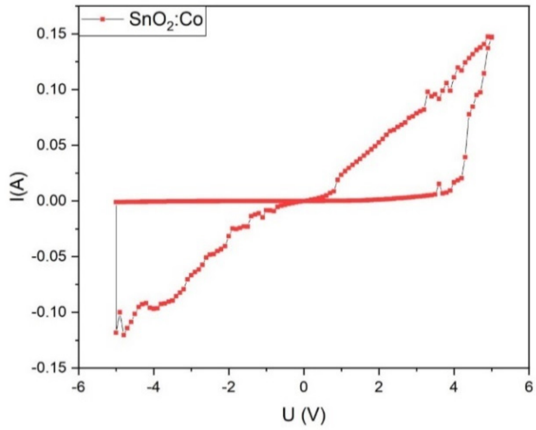

Figure 2. Current–voltage (I-V) curve of Ag/SnO_2: Co (1%)/SiO_2 /p-Si resistive switching

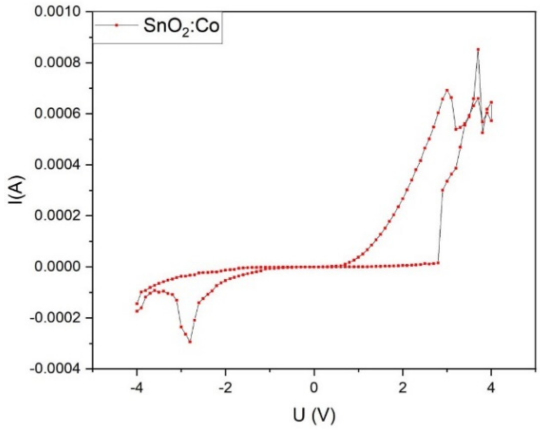

Figure 3. Current–voltage (I-V) curve of Ag/SnO_2: Co (5%)/SiO_2 /p-Si resistive switching

CONCLUSION

This study successfully demonstrated a tunable negative differential resistance (NDR) effect in memristors based on cobalt-doped tin dioxide (SnO_2:Co). The SnO_2:Co thin films, grown on p-type silicon substrates via ultrasonic spray pyrolysis (USP), exhibited unique electro-physical characteristics, demonstrating an unusual decrease in current within a specific voltage range. The identified NDR region, particularly within the positive voltage range (approximately +3V to +4V), highlights the promising potential of the devices studied. This behavior is attributed to the trapping of charge carriers and the redistribution of the electric field within the material.

The observed resistive switching properties, especially the stable transitions between high and low resistance states, indicate the suitability of these materials for memory applications. The presence of the NDR effect further creates new possibilities for these devices to be used in dynamic switching technologies, including low-power logic circuits and oscillation generators. The results position the Co:SnO_2 system as a promising candidate for controlled memory elements and future generation electronics.

Building upon the findings, further research is warranted to optimize the NDR effect and the device performance parameters. This includes fine-tuning the doping levels, film thickness, and the selection of electrode materials, as well as enhancing the device structure. Additionally, exploring the underlying mechanisms more deeply to stabilize the fabrication process and broaden the scope of applications is also crucial. These research directions could lead to finding new solutions for high-performance and low-power electronics. Our work provides a solid foundation for the future application of the Co:SnO_2 material in electronic devices, especially in memory and switching components.

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РЕГУЛЬОВАНИЙ ВІД'ЄМНИЙ ДИФЕРЕНЦІАЛЬНИЙ ОПІР У МЕМРИСТОРАХ SnO2:Co НА p-Si

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У цьому дослідженні досліджується явище від'ємного диференціального опору (ОДО) у мемристорах на основі діоксиду олова (SnO_2:Co), легованого кобальтом, виготовлених на кремнієвих підкладках p-типу. За допомогою ультразвукового розпилювального піролізу (USP) тонкі кристалічні плівки SnO_2:Co були нанесені на підкладки p-Si з тонким шаром рідного SiO_2. Отримані мемристорні пристрої демонструють відтворюване біполярне резистивне перемикання між високоомним (HRS) та низькоомним (LRS) станами. Ключові висновки включають спостереження чіткої області NDR (від'ємного диференціального опору) на вольт-амперних (ВАХ), зокрема в діапазоні позитивної напруги приблизно від +3 В до +4 В. У цій області NDR струм зменшується, незважаючи на збільшення напруги, що є характерною ознакою цього ефекту. Така поведінка пояснюється захопленням та перерозподілом заряду в матеріалі Co:SnO_2. Постійна та відтворювана природа спостережуваного ефекту NDR свідчить про потенціал мемристорів SnO_2:Co для застосування в передових технологіях пам'яті та комутації. Ця робота сприяє розумінню механізмів резистивного перемикання в тонких плівках SnO2, легованих кобальтом, які є перспективними матеріалами для пристроїв пам'яті наступного покоління.

Ключові слова: *легування кобальтом SnO_2; мемристор; комутація з негативним диференціальним опором; USP*