UV-induced resistive switching behavior of sol-gel based ZnO nanostructures

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Although zinc oxide (ZnO) is a well-known optoelectronic material, the study on switching properties with response to light emission is still limited. The recent work has shown a weak hysteresis response for an inject printed-based ZnO film after being shined with ultraviolet (UV) light. Addressing the issue, a sol-gel film-based ZnO memristor was fabricated and the bipolar effect of resistive switching (BERS) induced by a 254 nm UV illumination was investigated. The UV-Vis spectroscopy indicated that the ZnO thin film exhibited high absorption at 365 nm with a large energy gap of 3.23 eV, which is favorable for UV absorption and excitation. The current-voltage characteristics of the device shown a unique and significant behavior of negative differential resistance (NDR) effects after being illuminated by the UV light. The magnitude of the pinched hysteresis current loop is highly dependent on the exposure period of the UV light and the number of measurement cycles. This work could spark an idea of photo-induced memory devices in the future.

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1. Introduction

Zinc oxide (ZnO) has captivated numerous attention due to its versatility in many fields including healthcare, military, transportation, and semiconductor technology [1–6]. The main element of Zn is known as an abundant source, which is sustainable and offers significantly low cost in production. The dimension of the ZnO also can be varied to form quantum dots, nanowires, nanoparticles, and nanorods by controlling growth techniques and mechanisms, which tailor its functionality for various applications [7–11].

ZnO exhibit a wurtzite crystal structure with a large energy gap above 3 eV and very high excitation binding energy which is 60 meV at room temperature, which are suitable for optoelectronic application such as UV-sensor that operate in the ultraviolet region. Recently, triboelectric technology has improved the on/off ratio of Ag/ZnO/Ag from 590 to 10400 [12]. A high-sensitivity UV sensor based on ZnO nanorods grown on TiO2 seed layer films with responsivities of 1.70×10^{-1}A/W has been reported [13]. A flexible self-powered ZnO film UV sensor has been introduced which has an on/off current ratio of 1.3×10^6 even illuminated by a weak UV intensity of 0.1 mW/cm^2 [14]. Although the ZnO is commonly known as an n-type semiconductor with reasonably high electron mobility for transistors application, it is also a good insulator for memory devices. It is reported that a Li-doped ZnO-based resistive random access memory (ReRAM) shown stable bipolar resistive switching behavior at a low voltage range with a high switching current ratio and long retention up to 10^4 s [15]. An endurance and resistance stabilization of transparent multilayer resistance switching devices has been improved by inserting an oxygen-deficient WO_x layer and the heat-dissipating AlN buffer layer on ZnO-based ReRAM [16].

Notwithstanding this impressive progress, however, the impact of light illumination on resistive switching of ZnO nanostructures film is seldom investigated. Resistive switching of ZnO induced by visible light has been discovered [17]. Recently, the UV-induced memristor behavior on ZnO photodetector has been briefly discussed [18]. However, the hysteresis property was not significantly observed, due to the formation of crystal boundaries of the inkjet-printed ZnO film. In this present work, we demonstrated a significant hysteresis formation of the ZnO nanostructures planar device fabricated by the sol-gel technique induced by UV-light illumination. The influence of UV illumination on the shape and size of pinched hysteresis of the current loop was studied and discussed. This work provides preliminary insight on a multifunction UV-induced ReRAM application.

2. Experimental

An interdigitate-patterned indium thin oxide (ITO) substrate with a 50 μm electrode distance purchased from Ossila Ltd. was used in this work. The ITO substrate was ultrasonically cleaned with soap solution, acetone, isopropanol, and deionized water, subsequently before dried with nitrogen purged. ZnO sol-gel was synthesized as mention in our previous report [19–22]. The solution was then spin-coated on the cleaned interdigitated ITO substrate and pre-heated at 100 ^{o}C. The steps from coating to pre-heating were repeated three times. Finally, the

sample was then annealed in air at 500 ºC for an hour in a furnace. Fig. 1 shows the microscopic image of the ZnO thin film coated on the ITO substrate and a schematic diagram of the device structure illuminated with a 254 nm UV light. Form Fig. 1, the thickness of the ZnO nanostructures layer is 323 nm.

Surface morphology, cross-section images, and thickness of the films were obtained by field-emission scanning electron microscopy (FESEM) (Joel JSM-7600F). Optical transmission and absorption properties were characterized by using UV-Vis (Perkin Elmer Lambda 750). The current-voltage and photocurrent properties of the device were characterized by using a source measure unit (Keithley 2600) and a 254nm UV-light source.

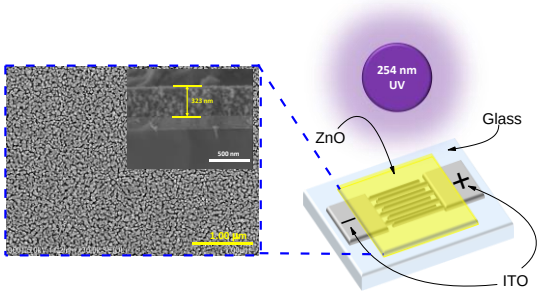

Fig. 1. FESEM image of ZnO thin film and schematic diagram of the device under UV radiation (color online)

3. Results and discussion

Fig. 2 shows the transmittance and absorption spectrum of the ZnO thin films. The film exhibits high transparency above 90% in the visible range of 400 to 800 nm and has a strong absorption at 365 nm. This indicates that the ZnO film is suitable for detecting UV radiation, however less sensitive to sense the visible light emission. From the absorption data, the Tauc relation was plotted as presented in insert Fig. 2 to determine the optical energy gap of the film. The optical energy gap of the film obtained is 3.23 eV, which is similarly reported in [20]. The high band energy gap can be tuned by doping and annealing processes to alter the optoelectronic properties of the ZnO.

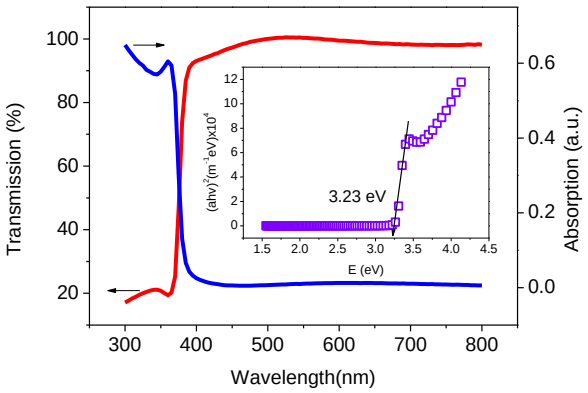

Fig. 2. Optical transmission and absorption spectrum of the ZnO thin film. Insert is the Tauc plot (color online)

Fig. 3(a) shows the I-V curve of the device in the dark condition in the log scale. The voltage cycle is from 0 V to 5 V and then reversed to -5 V before being returned to 0 V. A pinched hysteresis of current was obtained when the device was biased, which indicates the ZnO device exhibit a bipolar memristor behavior [23, 24]. A clear set phenomenon is observed at 3 V while a reset process occurs at a voltage of -3 V. However, the current hysteresis loop in the positive voltage region was bigger than the negative voltage region.

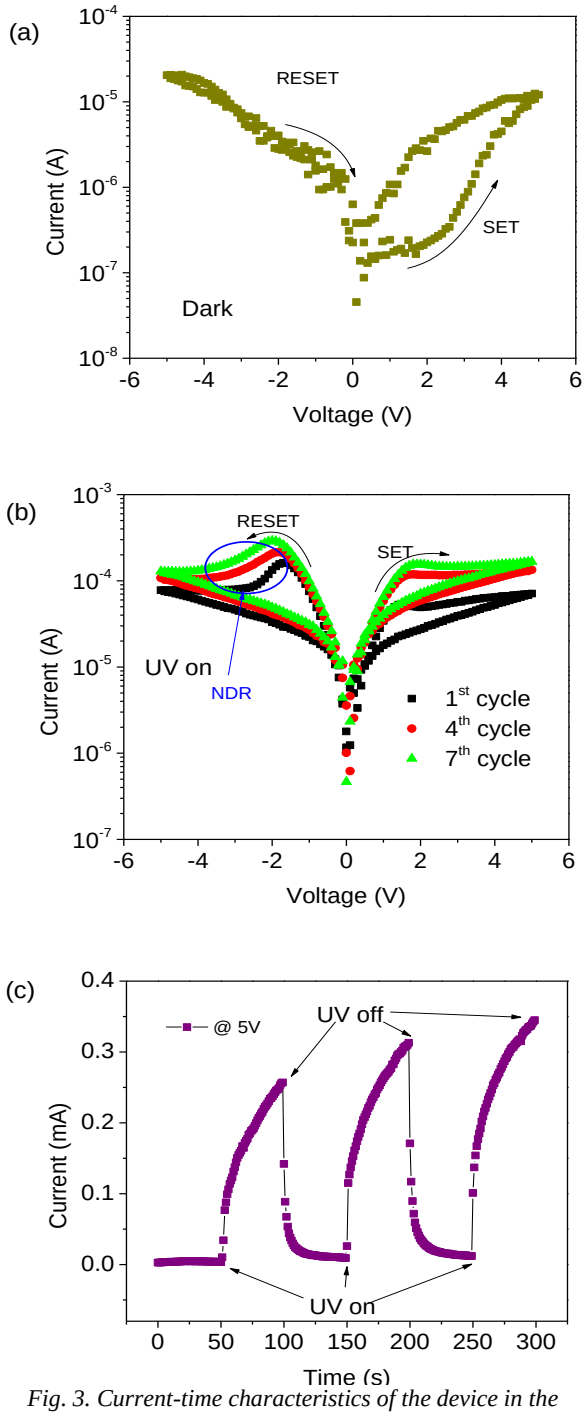

Fig. 3. Current-time characteristics of the device in the (a) dark and (b) UV-illuminated condition, and (c) time-resolved UV photocurrent on/off plot of the device biased at 5V (color online)

Interestingly, when the device was exposed to the 254 nm of UV light, the shape of the hysteresis loop properties

significantly changed as compared to the dark condition, as shown in Fig 3(b). The size of the current loop in the negative voltage region is now bigger as compared to the positive voltage region. An anomalous I-V curve is observed when the device was in the reset condition, where the current reduces after reached its maximum value. This behavior is known as negative differential resistance (NDR), in which this type of memristor characteristic was reported in [25]. The NDR phenomenon also been reported in organic light-emitting diode [26]. After UV illumination, the set voltage (V_{set}) and reset voltage (V_{reset}) were reduced to 1.6 V and -1.6 V, respectively, from the value of 3 V and -3 V, respectively as in the dark condition. However, when the number of measurement cycles was increased, the set and reset voltage are observed to increase up to 1.9 V and -1.9 V, respectively. Additionally, the size and magnitude of the current hysteresis loop are noticed to be larger and higher, respectively. It has been reported that a high number of cycles will increase the rapture/formation of conducting filaments [27]. The presence of UV light has excited the electron to form an electron-hole pair or known as an exciton. This exciton creates a free electron that could assist in the rapture/formation of conducting filaments. A combination of a high number of cycles and exciton formation induced by UV illumination has resulted in bigger hysteresis current loop. The shape difference between the on and off conditions in this work is much significant as compared to the previous report [18].

Fig. 3(c) shows the time-resolved UV photocurrent on/off measurements of the device at a bias of 5 V. The device shows a double exponential rise and decay under illumination. This indicates that two mechanisms may be attributed to the double exponential rise and decay [28]. When the UV light was turned on, is observed that the photocurrent continuously rises, until the light was shut down. There is no saturation current observed for every UV-on cycle. Additionally, the maximum current is increased as the number of on/off cycles increased. Besides, the recovery process was reasonably fast and the dark current value was almost stable to its minimum after 20 seconds the UV light was off. Since the applied voltage is higher than the set voltage, the formation of the conducting filament during the ON state has facilitated the electron charge to travel from the positive to the negative electrode. There is also a possibility of high absorption of oxygen on the surface of the ZnO nanostructure film due to the planar construction of the device. The absorbed oxygen can increase the concentration of the electron charged which then increases the photocurrent when the number of cycles increases.

4. Conclusions

UV-induced ZnO nanostructure resistive memory device was demonstrated. The effects of 254 nm UV-light on its resistive switching were investigated. The resistive switching profiles of the device can be stimulated by UV illumination. The shape and magnitude of the hysteresis current loop are highly dependent on the period of UV illumination and the number of measurement cycles. The stability and sensitivity of the device remain a challenge for future work.

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