Resistive Switching Tuning Ferromagnetism and Near Band Edge Emission in Metal/ZnO:Cu/n+–ZnO:Ga/c-Sapphire Structure

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(Received November 14, 2018; revised version January 29, 2019; in final form March 6, 2019)

A metal/ZnO:Cu/n+–ZnO:Ga/c-sapphire structure was fabricated using the pulsed laser deposition. With biased applied across the metal and the n+–Ga-doped ZnO whereas the Ga-doped ZnO was grounded and \(I–V\)-measurement conducted with the voltage sequence of 0 V \(\rightarrow\) +ve bias \(\rightarrow\) 0 V \(\rightarrow\) -ve bias \(\rightarrow\) 0 V, resistive switching was observed while the resistance transited from high state to low state at \(\approx +1.5\) V and reset to high state while the sample was reversely biased. SQUID measurement shows that the sample is ferromagnetic at room temperature, and the magnetic moment is tunable, having a reduction of \(\approx 30\%\) during the high state to low state switching.

X-ray photoelectron spectroscopy study shows an increase in Cu\textsuperscript{+}:Cu\textsuperscript{2+} oxidation state ratio during the high state to low state transition. Similar resonance state tunable on near band edge emission intensity is observed, with the intensity reduced by \(\approx 30\%\) during the high state to low state transition but the defect emission intensity does not change. The physics leading to the resonance state tuning of magnetic moment and near band edge emission intensity is discussed.

DOI: 10.12693/APhysPolA.136.122

PACS/topics: ferromagnetism, near band edge emission, Cu-doped ZnO

1. Introduction

Defect mediated room temperature ferromagnetism (RTFM) and materials with magnetization tunable by external electric bias are attractive and interesting physical phenomena not only in the fundamental aspect but also in terms of having impact in applications. In the aspect of UV emitting devices, electric bias tuning near band edge (NBE) emission is also an attractive phenomenon for applications. ZnO is a wide band gap semiconductor having potential applications in optoelectronic, transparent conductive electrode, transparent electronic, and spintronics, etc. [1].

Cu-doped ZnO is particularly interesting because neither its, nor its oxide are FM at RT. Herng et al. [2] proposed a microscopic indirect double exchange model for explaining the FM in Cu-doped ZnO, in which the FM is aligned by the electron hopping between the Cu having +1 and +2 oxidation states (Cu\textsuperscript{+} and Cu\textsuperscript{2+}) in the vicinity of the overlapping V\textsubscript{O} orbitals. Figure 1a shows the schematic diagram of this exchange (the black arrow).

The Cu\textsuperscript{(+2/2+)} is the energy level for the oxidation process Cu\textsuperscript{+} \(\rightarrow\) Cu\textsuperscript{2+}+e, in which the doubly filled state refers to Cu\textsuperscript{2+} and the singly filled state refers to Cu\textsuperscript{2+} [3]. The occupancy of Cu\textsuperscript{+}:Cu\textsuperscript{2+} ratio is indeed dependent on the Fermi level position \(E_F\). As the FM rises from the Cu\textsuperscript{2+}–V\textsubscript{O}–Cu\textsuperscript{+} coupling which involves one Cu\textsuperscript{2+} and one Cu\textsuperscript{+}, it is thus expected that Cu\textsuperscript{2+}:Cu\textsuperscript{+} equal to 1:1 would yield the maximum magnetization. This gives rise to our thought of tuning the magnetization of the Cu-doped ZnO sample by changing the Fermi level through resistive switching.

![Fig. 1. The schematic diagram showing the Cu\textsuperscript{+}–V\textsubscript{O}–Cu\textsuperscript{2+} coupling which leads to the RTFM of Cu-doped ZnO. The coupling involves the hopping of an electron from the Cu\textsuperscript{+} to the Cu\textsuperscript{2+} through the nearly overlapping V\textsubscript{O} orbital.](image-url)
2. Experiment

The Cu-doped ZnO film samples (≈ 300 nm thickness) used in this study was grown on c-plane sapphire by pulsed laser deposition (PLD) with the details given in [4, 5]. We have carried out the systematic study on the effect of the different oxygen growth pressure \( \text{PO}_2 \) (0, 0.015, 0.020, and 0.050 Pa) and the Cu weight compositions in target (1%, 2%, and 4%). All the samples exhibit wurzite structure with (002) as the preferential direction.

3. Results and discussion

Figure 2 shows the data of the magnetization against applied field of the samples with Cu = 2 wt% and different \( \text{PO}_2 \) (= 0, 0.015, 0.020, and 0.050 Pa) measured at room temperature by a Quantum Design SQUID-VSM. The sample grown with \( \text{PO}_2 = 0.02 \text{ Pa} \) is clearly FM at RT which has saturated magnetization of 1.1 \( \mu_B \)/Cu, and the others are effectively not magnetic. This saturated magnetization is close in magnitude to the value of \( 0.5 \mu_B \)/Cu reported by Herng et al. [2]. The magnetization is very sensitive towards \( \text{PO}_2 \), and thus would not favor effective ferromagnetic electron hopping. The XAS data is not included in the manuscript but will be presented in an upcoming manuscript.

Although the sample grown with \( \text{PO}_2 = 0.02 \text{ Pa} \) is RTFM, the observation of RTFM is a necessary but not sufficient indication for revealing intrinsic FM as the FM could be originated from the secondary phase. To detect the magnetic secondary phase, we have performed detailed and careful X-ray diffraction study and identified the presence of CuO (111) and (022) peaks with very small intensities [4]. Moire’s fringe was also identified in transmission electron microscopy (TEM) study, which would indicate the presence of the CuO nanocrystal with size of ≈ 5–6 nm. Zero-field cooled (ZFC) and field-cooled (FC) magnetization measurement also coincides with small size CuO nanocrystal acquiring FM due to the residual spin of Cu ions at the cluster interfaces [4, 6]. This implies that CuO nanocluster contributes for the RTFM, but we cannot exclude the possibility that part of the FM originates from the intrinsic origin.

With the aim to achieve resistive switching tuning magnetization, a sample with the structure of Al/ZnO:Cu/ZnO:Ga/sapphire was fabricated with its schematic diagram shown in Fig. 3a. Ga-doped ZnO (GZO, Ga = 2 wt%) with thickness of 100 nm and resistivity ≈ 10^{-4} \( \Omega \) cm was grown on c-plane sapphire by PLD and this thin film was used as the conducting electrode. With \( \text{PO}_2 \) of 0.02 Pa, Cu-doped ZnO (Cu = 2 wt%) with thickness of 300 nm was then grown on the GZO film by PLD. Al metal electrode was then thermally evaporated onto the ZnO:Cu film. The \( I-V \) data of this structure as shown in Fig. 3a exhibit resistive switching. As the applied bias increases from zero volt the resistance is high (path 1 in Fig. 3). As the applied bias reaches \( \approx +1.5 \text{ V} \), the resistance switches to low (path 2). The subsequent decrease of applied bias has the memory effect that the resistance keeps low. The resistance of the device can be reset to high resistance by applying a negative bias (paths 4 and 5). The resistances of the high resistance states (HRS) and low resistance states (LRS) are respectively \( \approx 1 \text{ M}\Omega \) and \( \approx 0.1 \text{ M}\Omega \). The memory effect is found to be non-volatile. That is after the device is set to low resistance state (LRS) by the +1.5 V forward bias and then with the applied bias removed. Then after 5 h, the \( I-V \) testing of the device with a small positive bias < 1.5 V shows that the device is still in the LRS.

Resistive switching in transition metal oxide has been extensively studied with its potential application as resistance random access memory [7]. The resistive switching is attributed to the formation of a conducting filament (like VO), and the electronic properties in the vicinity of the metal/oxide interface [7]. However, it is worthy to bring out that the present sample structure is not quite the same as that used in the typical resistive switching study. The active Cu–ZnO layer used in the present study has the thickness of 300 nm and that in the typical resistive switching device is ≈ 20 nm. It is thus less likely that the formation of the VO conducting filament would form through such a long distance in our thick film, and moreover the electric field which drives the VO is smaller in the thick film. Although the mechanism

Fig. 2. The magnetization against the applied field for the Cu doped ZnO samples grown with different oxygen pressures. The composition of the Cu is 2 wt%.
leading to the resistive switching reported in the present study still requires further study for understanding the detailed physics behind, it is worthy to carry out the CV measurement to reveal the electronic properties at the interface. Figure 3b shows the CV data corresponding to the set-reset process of the HRS and LRS, for which hysteresis behavior is found. It is noticed that the capacitance in the as-received state (i.e. HRS and path 1 in the figure) is lower than that after setting to LRS (paths 2 and 3). For the Schottky contact, the capacitance \( C \) is related to the depletion width \( W \) by \( C = \varepsilon_0 \varepsilon S/W \), where \( S \) is the device area. This implies that the depletion width for the HRS is larger than that of the LRS, and thus the tunneling current during the HRS is smaller than that during the LRS. This may explain the observation of the switching.

The SQUID measurement was carried out to characterize the magnetization against the applied field while the sample was as-received (in HRS), set to LRS by applying a positive bias, and then reset to HRS by applying a negative bias [5]. The sample used for studying the magnetic property was slightly different from that used for the resistive switching study, whereas array of Al/ZnO:Cu/ZnO:Ga/sapphire cells were fabricated by evaporating an array of Al metal circular contacts having diameter of 250 \( \mu \)m, fabricated on top of the ZnO:Cu film while each of the Al metal contacts were separated by 250 \( \mu \)m (see inset in Fig. 4). The set voltage for switching all the cells in the array to LRS was +4 V, and the re-set voltage for switching all the cells in the array from LRS back to HRS was −4 V. It has been verified that the resistive states upon setting or re-setting were stable for over 5 h after the external electric bias was removed. The room temperature SQUID measurements were performed immediately after the cell array was set to the resistive state and the applied bias was removed during the SQUID measurement. The details of the experiment can be found in Ref. [5]. The \( M-H \) hysteresis curves for the cell array in the as-received state (i.e. HRS), after they were switched to LRS by applying a +4 V across the Al and GZO contacts, and subsequently re-setting back to HRS by applying a −4 V were shown in Fig. 4. The saturated magnetic moment of the cell array in the as-received state (i.e. in HRS) is \( 2.1 \times 10^{-6} \) emu, and it drops to \( 1.6 \times 10^{-6} \) emu after the cells were set to LRS by applying the +4 V, then increases back to \( 2.0 \times 10^{-6} \) emu after the cells were re-set back to HRS by applying the −4 V. The saturated magnetizations of the different resistance states were tabulated in Table I.

XPS was carried out to reveal the \( \text{Cu}^+ : \text{Cu}^{2+} \) ratios while the cell array was in the states of as-received (HRS), set to LRS by applying the +4 V, and then re-set back to HRS by applying the −4 V. The \( \text{Cu}^+ : \text{Cu}^{2+} \) ratio is obtained by fitting the intensities of the \( \text{Cu}^+ \) and
The relative saturated magnetization, Cu\(^{2+}\):Cu\(^{2+}\) ratio and relative V\(_O\) intensity of the Al/ZnO:Cu /GZO/sapphire sample while as-received (HRS), set to LRS by applying positive bias, and then reset to HRS by applying reverse bias.

<table>
<thead>
<tr>
<th>Saturated magnetic moment [emu]</th>
<th>Cu(^{2+}):Cu(^{2+}) ratio</th>
<th>Relative V(_O) intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>as-received HRS (≈ 1Ω)</td>
<td>2.1 × 10(^{-6})</td>
<td>4.4</td>
</tr>
<tr>
<td>+ve bias set to LRS (≈ 0.1Ω)</td>
<td>1.6 × 10(^{-6})</td>
<td>6.9</td>
</tr>
<tr>
<td>-ve bias reset to HRS (≈ 1Ω)</td>
<td>2.0 × 10(^{-6})</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Cu\(^{2+}\) components of the Cu 2p\(_{3/2}\) and the Cu 2p\(_{1/2}\) XPS spectra and the details and XPS spectra were shown in Ref. [5]. The results are tabulated in Table I. Cu\(^{+}\) is significantly more than Cu\(^{2+}\) irrespective of the resistance states. As the device is switched from as-received HRS to LRS by applying the +ve bias, the Cu\(^{+}\):Cu\(^{2+}\) ratio increases from 4.4 to 6.9. As the device is then reset from the LRS to the HRS by applying the−ve bias, the Cu\(^{+}\):Cu\(^{2+}\) ratio restores to the value of 4.6 which is close that of the as-received HRS.

To monitor the V\(_O\) while the sample was in the different resistance states, the O 1s XPS spectra were fitted with three Gaussians. The intensities of the V\(_O\) related component while the device was at different resistance states are tabulated in Table I. No significant change in the relative V\(_O\) intensity is observed irrespective of the resistance states.

As summarized in Table I, the saturated magnetization and the Cu\(^{+}\):Cu\(^{2+}\) ratio are independent on the resistance state of the device, for which the relative saturated magnetization and the Cu\(^{+}\):Cu\(^{2+}\) are respectively ≈ 1.0 and ≈ 4.5 while in the HRS, and equal to ≈ 0.7 and 6.9 while in the LRS. It would be worthy to discuss the physics behind the resistive switching tuning magnetization. The RTFM of Cu-doped ZnO is attributed to the carrier hopping between the Cu\(^{2+}\) and Cu\(^{+}\) through the nearby V\(_O\) orbital [2]. As in such a Cu\(^{2+}\)–V\(_O\)–Cu\(^{+}\) coupling, one Cu\(^{2+}\) and one Cu\(^{+}\) are involved. It implies that maximum coupling and thus magnetization will result if the Cu\(^{+}\):Cu\(^{2+}\) ratio is equal to unity. The Cu\(^{+}\):Cu\(^{2+}\) is always significantly larger than 1 either in the HRS and LRS. Switching from HRS to LRS results in more carrier injection and thus the Fermi level moves towards the conduction band. This would increase the Cu\(^{+}\) occupancy and decrease that of the Cu\(^{2+}\), and thus increase the Cu\(^{+}\):Cu\(^{2+}\) ratio. This deduction is also confirmed by the experimental XPS measurements. While the V\(_O\) concentration does not significantly change with the resistance state, increase of Cu\(^{+}\):Cu\(^{2+}\) ratio implies even more deviation from the 1:1 ratio (corresponding to maximum magnetization) and thus the saturated magnetization drops.

Photoluminescence characterization of the samples at HRS and LRS were performed at 10 K. To facilitate the PL experiment, the sample configuration is shown in the inset of Fig. 5. The excitation laser is incident from the side of the sapphire. The thicknesses of the GZO and ZnO:Cu layers are respectively 50 nm and 400 nm. The PL spectra taken at HRS and LRS have the same luminescence peaks but the intensities are different. NBE peaks of 3.15, 3.22, and 3.32 eV, and defect emission at ≈ 2.36 eV are observed in both of the spectra. I–V measurement was conducted after the PL measurement and it was found that the resistance state was not changed by the PL measurement. As the ZnO:Cu film has thickness as 400 nm, the PL signal is originated from the GZO films, the GZO/ZnO:Cu interface, or the ZnO:Cu film, but not from the ZnO:Cu/Al interface. However, the PL peaks found in the present sample are also found in the PL spectrum of the bare Cu-doped ZnO sample grown in the same condition but not in that of the bare GZO sample. This implies that the PL signal observed here originates from the depletion region or the bulk in the ZnO:Cu film.
to structural defects (pages 44 and 45 in [1]). As the sample is switched from HRS to LRS, the depletion width decreases. Some defects (say donor) located in the depletion region during the HRS may change their charge state by emitting an electron to the conduction band during the shrinking of the depletion width. If this defect is involved in the transitions of the NBE emissions, change of charge state may cause the corresponding photon emitting transition processes to be no longer feasible and thus the NBE emission intensity decreases. However this explanation is speculative and further investigation is needed to explore the physics behind.

4. Conclusion

Resistive switching tuning RT FM was observed in Cu-doped ZnO based structure. Switching from HRS to LRS results in reduction of saturated magnetization. The change of the RT FM is due to the increase of the Cu⁺:Cu²⁺ occupancy which reduce the Cu⁺:VO-Cu²⁺ coupling which leads to the RTFM. Switching from HRS to LRS also leads to the reduction of the NBE emission intensity, which is speculated to be related to the change of charge state of the defects involved in the NBE emission transitions.

Acknowledgments

This work is financially supported by the HKSAR RGC GRF (17302115).

References