Effect of Mg Doping on the Electrical Characteristics of High Performance IGZO Thin Film Transistors

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In this work, we report that the electrical characteristics of Indium-Gallium-Zinc-Oxide Thin Film Transistors (IGZO-TFTs) can be improved by Mg doping in the IGZO layer. Several composite IGZO/Mg-doped IGZO channel structures were employed. With appropriate Mg-doped IGZO thickness, the electrical properties such as mobility, subthreshold swing (S.S.) and on/off ratio can be significantly improved by Mg doping. Mg doping in IGZO layer can stabilize device performance whatever the device is stressed under positive gate bias or negative gate bias with illumination. By X-ray photoelectron (XPS) analysis, we observe the presence of Mg can change the oxygen bonding states and influence the properties of IGZO layer. The atomic percentage of Mg in the IGZO layer is about 6.53%. As a result, Mg doping is a useful method to enhance the performance and stability of IGZO-TFTs.
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IGZO thin film transistors have attracted industrial and commercial interests in recent years and now there have already been new products using IGZO. It has the advantages including low temperature processing, large area fabrication and being compatible with flexible electronics.[1] Its wide applications to flexible electronics, TFTs, electronic papers and sensors make amorphous oxide semiconductors (AOS) have the possibility to be the prevailing material of next generation TFT technology.[2] Even though there are many kinds of AOS materials, IGZO is one of the most promising candidates. The TFTs with IGZO channel layer usually exhibit superior electrical performance such as high channel mobility, a good on/off ratio, a small S.S. and an acceptable threshold voltage (V_T).[3] These features make IGZO be more attractive than other materials such as amorphous silicon, poly-silicon and organic conjuagated polymers for the TFT technology.[4]

Recently, many scientists have been focusing on understanding and improving the properties of IGZO layer by many different ways. Some focused on the IGZO composition adjustment; they tried to find the optimized electrical performance by understanding what kinds of function these atoms have in the oxide semiconductor.[5,6] Some groups focused on varying oxygen flow during deposition because the properties of IGZO are known to be very sensitive to the deposition condition.[7] Also, Kim et al. tried to replace the metal atom in the IGZO layer by other kind of metal element, for example, Hf-In-Zn-O (HIZO).[8] The purpose of all the researches is to make the AOS material have better electrical performance and more stable reliability such as bias, illumination and environment-stabilities.

In this work, we systematically investigate the effect of Mg doping on the electrical properties of IGZO-TFTs. We find the TFTs with composite IGZO/ Mg-doped IGZO channel structure possess better electrical performance than that of the conventional IGZO-TFTs in the aspects of on/off ratio and S.S.. By XPS analysis, we observe the presence of Mg can change the oxygen bonding states and influence the properties of IGZO layer. As a result, the electrical performance of the IGZO-TFTs can be improved by using the composite IGZO/Mg-doped IGZO channel.

In this study, we used bottom-gate top-contact device structure. After standard RCA cleaning, we used an n^{++} Si wafer as the starting substrate and its back side was coated by Al as the gate electrode. A 200 nm SiO$_x$ layer was formed by plasma enhanced chemical vapor deposition system and its capacitance was 1.38×10^{-8} F/cm^2. Then, we defined the channel region by sputter and lithography. The device channel width and length were 200 and 50 μm, respectively. In this step, we employed two different recipes to deposit the channel layer. One was Mg and IGZO co-sputter (M-I) and the other was IGZO (I) sputter only. In other words, we varied the channel structure. The DC power for Mg and IGZO targets were 50 W and 70 W respectively.

The Ar/O$_2$ ratio was 24/6 SCCM (SCCM denotes cubic centimeter per minute). Keeping the thickness of active layer to be c.a. 30 nm, the different combinations were 300 Å I (Sample A), 10 Å M-I +290 Å I(Sample B), 50 Å M-I +250 Å I (Sample C), and 300 Å M-I (Sample D), respectively. After the channel deposition, we defined source and drain electrodes region by lithography and deposited 50 nm Ti film by E-gun; the device channel width and length were 200 and 50 μm, respectively. All samples were annealed at 300 °C with N$_2$ flow for 30 minutes. The transistor performances were measured by HP4156 semiconductor parameter analyzer, the drain voltage was set to 5 V and the gate voltage was swept from −20 V to 20 V. We also measured its output characteristics with the drain voltages from 0 V to 20 V and the gate voltage variation between 0 V to 20 V in steps of 5 V. The thin film properties were measured by XPS.

Figure 1 shows the transfer characteristics of our IGZO TFTs. Table I summarize the electrical parameters for all the samples. All parameters are obtained based on the conventional transistor current equation. We can see sample A in which the channel was composed of pure IGZO depicts good electrical performance. The carrier mobility is of 12.29 (cm^2/V sec), the S.S. value is of 461 (mV/decade), the on/off ratio is of 1.62×10^8 and the V$_T$ is of −2.1 V. All these parameters of sample A indicate that the performance of our control IGZO TFTs is comparable with those reported in the other works.[9,10] It can be found the electrical performances of sample B are better than sample A, it means Mg doping can improve the IGZO-TFT performances. We also measured the Hall mobility and carrier concentration. The Hall mobility for IGZO and Mg-doped IGZO is 15.37 and 26.13 (cm^2/V sec) and the carrier concentration is 1.43×10^{18} and 9.18×10^{17}(/cm^3), respectively. Mg doping can reduce the carrier concentration because of the reduction in oxygen vacancy density, but increase the Hall mobility resulting from the bonding state change in the IGZO layer. The properties of the IGZO-TFTs are mainly determined by the ZnO system[11] so that we can explain what we have observed in the Mg-doped IGZO-TFTs according to the results in the ZnO system.
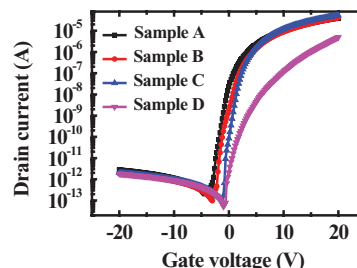

Figure 1. Transfer characteristics I_D-V_G of TFTs with different thickness of Mg-doping. The channel length and width of devices are 50 and 200 μm.

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Table I. Comparison of the various parameters for the sample A, B, C and D.

Sample	V_T (V)	Mobility (cm^2/ V sec)	S.S. (mV/decade)	On/Off ratio
Sample A	−2.1	12.29	461	1.62×10^8
Sample B	−1.3	16.81	347	4.29×10^8
Sample C	0.2	17.36	331	5.96×10^8
Sample D	4.9	4.97	355	1.09×10^8

Figure 3. Extrapolated bandgap values for IGZO and Mg-doped IGZO films by the transmittance spectra.

Remashan et al.[12] reported the Mg doped ZnO as a buffer layer can improve the electrical performances of the ZnO-TFTs; they attributed to the resultant grain size with the addition of Mg doping. The larger the grain size, the lower defect density in the IGZO is. This is consistent with our measuring results. Besides, the Mg^{2+} substitution in the Zn^{2+} site does not lead to significant lattice distortion due to their similar ionic radii.[13] Therefore, Mg atoms can effectively be doped in the IGZO system and improve the electrical performances. Clearly, samples B and C have higher on/off ratio, lower V_T near 0 V, larger mobility and smaller S.S. value with the comparison of sample A. These results imply that Mg doping can change the bulk property of IGZO, which is closely related to the bonding states in IGZO; it does not degrade the property of the interface between the IGZO channel and the SiO$_x$ dielectric layer. However, with increasing the thickness of Mg-doped IGZO layer to 30 nm (Sample D), we can observe the degraded electrical performance, such as obvious on current reduction and moving away of V_T from 0 V. These results are similar to those in the paper reported by Remashan et al.[12] and might be attributed to an increased effective mass of the electrons.[14] Hence, Mg doping in the IGZO layer can improve the transistor performance effectively and be able to adjust V_T toward the positive direction. Besides, the thickness of Mg-doped IGZO layer shall be optimized.

Figure 2 shows the output characteristics of all samples. It should be noted that the drain current scale of sample D is different from those of the other samples. It can be observed the currents of samples A, B and C saturate in high drain voltages under each gate voltage. But, it is different for sample D; its current does not saturate in high drain voltages, especially under high gate voltages. We also checked the contact resistance by transmission line method (TLM).[15] The contact resistances for sample A, B, C and D are 598, 538, 497 and 3317 (Ω-cm), respectively. These values, especially for sample D, mean that the Mg doped IGZO layer does not form a good contact with the Ti electrodes. We think there might be the formation of oxide at the interfacial layer between the Mg-doped IGZO and Ti. The oxide resulting from the Ti deposition certainly degrades the conductivity and the addition of Mg in IGZO even makes this situation worse. In
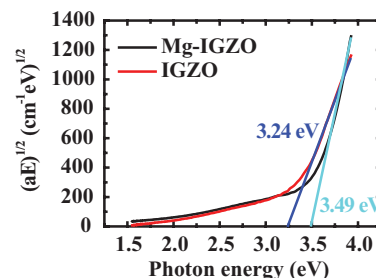
other words, we can say that the potential barrier between Ti and the Mg-doped IGZO layer is higher than that between Ti and the undoped IGZO, and then increases the difficulty of carrier injection from the Ti electrode into the Mg-doped IGZO layer. This might be ascribed to the grain size resulting from Mg doping. Fang et al. have ever reported that the grain size of ZnO is highly dependent on the ratio of Mg doping.[16] The defect density is closely related with the grain size; the Mg-doped IGZO layer in this work is supposed to have small grains and thus high defect density. We think they do not influence the electrical performance during device operation because the impact of defects can be significantly suppressed by the large amount of accumulation carrier. However, the defects can affect the carrier injection from the electrode to the active layer. Hence, the contact between Ti and the Mg-doped IGZO layer is deteriorated. Therefore, the effect of Mg doping can increase the electrical performance of IGZO-TFTs and improve the interface between the IGZO and SiO$_x$ layer. However, Mg-IGZO layer cannot form good contact with Ti. The situation at the interface between the Mg-doped IGZO and Ti is quite complicated so that it should be further investigated.

Figure 3 shows the extrapolated bandgap values for the undoped IGZO and the Mg-doped IGZO films by the transmittance spectra. The bandgap of IGZO is increased from 3.24 to 3.49 eV with the addition of Mg during sputter process. There might be the formation of MgO$_x$ during the Mg-doped IGZO deposition by the co-sputter process. MgO$_x$ is not conductive and belongs to the wide bandgap materials. The bandgap of MgO$_x$ is 7.8 eV which is higher than that of IGZO.[17] The bandgap of IGZO can be widened by the existence of MgO$_x$. The formation of MgO$_x$ can suppress the oxygen vacancy generation and change the oxygen bonding states in IGZO, which is beneficial in stabilizing the IGZO-TFTs during operation. The ratio of MgO$_x$ shall not be too high to degrade the property of IGZO thin film.[18] Therefore, the effect of Mg doping on the IGZO can improve the electrical performance of the IGZO-TFTs.

Figure 4 shows the transfer curve shift of all samples as a function of gate bias stress duration. The stress voltage was 20 V. We can clearly observe that there is no obvious S.S. change after stressing; implying there is no new traps created at the interface during stress. The V_T shift for samples A, B, C and D is 4.6, 3.4, 1.2 and 1.3 (V), respectively. The suppression of V_T shift by Mg doping is remarkable when the thickness of M-I layer is above 50 Å. Mg doping can help in forming MgO$_x$ in IGZO and in turn suppress the oxygen vacancy generation. The oxygen vacancies are thought to be able to give the electrons during stress; the V_T shift is caused by the electron trapping inside the gate dielectric and the interface between the channel and the gate insulator. Since MgO$_x$ has very strong Mg-O bond, the electrons thus are suppressed during operation. Hence, Mg doping in IGZO can improve the reliability of the IGZO-TFTs against the positive bias stress. The reduction in oxygen vacancy density by adding Mg into IGZO will be addressed in the following statement.

Figure 5 shows the transfer curves of all samples as a function of gate voltage for various stress durations under white light illumination. The stress voltage was −20 V. The V_T shift for samples A, B, C and D is −6.1, −3.4, −2.8 and −1.2 (V), respectively. The tail curve just as when the device is turned on can be observed in sample A after
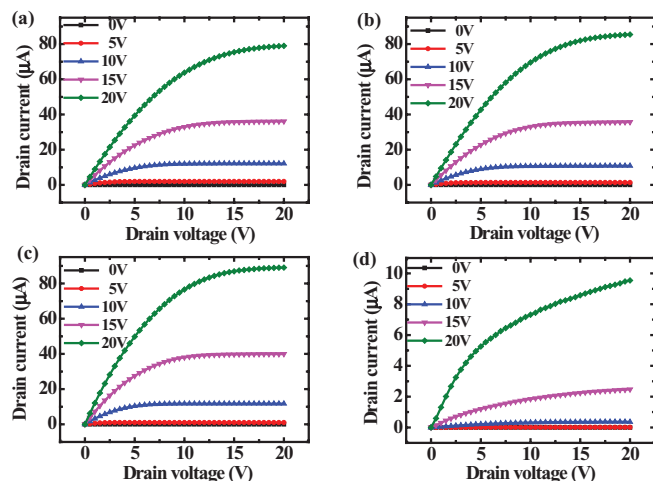
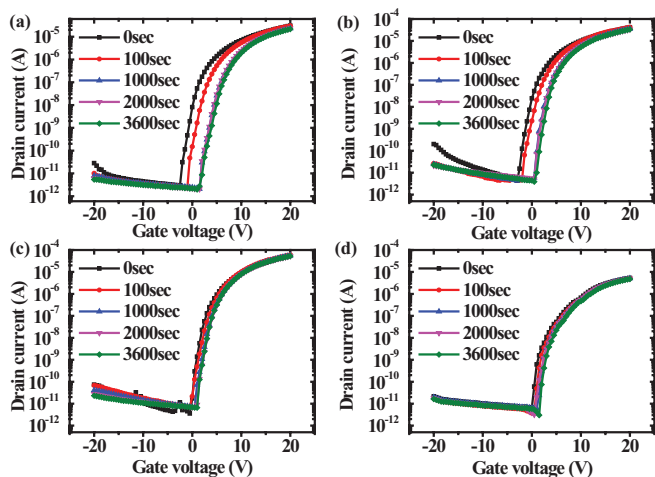**Figure 2.** I$_D$−V$_D$ output characteristics of sample A, B, C and D.

Figure 4. Transfer curves of the IGZO-TFTs as a function of stress time for samples (a) A, (b) B, (c) C and (d) D. Stress was performed with a gate bias of 20 V.

a certain time stress under illumination. However, this abnormality can be suppressed when Mg doping is added in the IGZO layer. The mechanism of degradation is caused by the electron-hole pair generation under illumination. The shorter the wavelength, the severer the degradation is.[19] The negative gate bias can lead to hole trapping inside the gate dielectric and the interface between the channel and the gate insulator. Since Mg doping in IGZO can lead to the formation of MgO_x, the bandgap of IGZO thus increases. Higher bandgap can reduce the electron-hole pair generation under the illumination with the shorter light wavelength; the stability of the IGZO-TFTs for the negative bias stress under illumination can then be improved. As a result, we speculate that the MgO_x formation might be main factor in stabilizing the reliability of the IGZO-TFTs under negative bias stressing with illumination after the addition of Mg atoms.

Figure 6 illustrates the O_{1s} XPS narrow scan spectra of the IGZO thin film with and without Mg doping. It should be noted that all data have been calibrated with respect to the carbon signal. There is no obvious shape change for In, Ga and Zn elements (data not shown) implying that Mg elements do not interact with other metal elements in the IGZO layer. Besides, the atomic percentage of Mg in the IGZO layer is about 6.53%, which means Mg is still the minor element in the IGZO layer. Therefore, we assume the structure of IGZO with minor Mg doping will not change significantly and remains similar to that
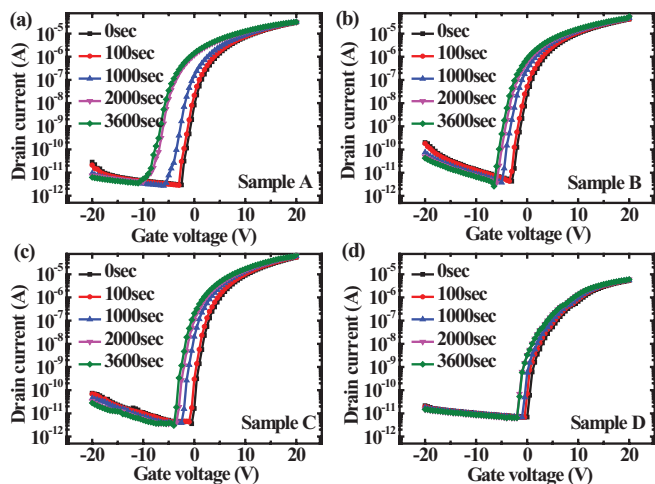

Figure 5. Transfer curves of the IGZO-TFTs as a function of stress time with light illumination for samples (a) A, (b) B, (c) C and (d) D. Stress was performed with a gate bias of −20 V.
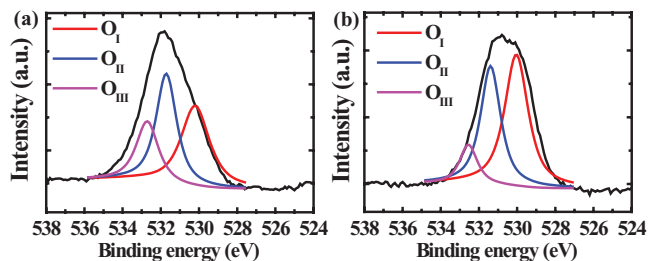

Figure 6. O 1s XPS narrow scan spectra on the IGZO thin film surface with- and without Mg doping and its bonding states analysis.

of undoped IGZO. The $O1_s$ signal has an obvious shape change and becomes broader after the addition of Mg. MgO_x is not conductive and its presence can widen the energy bandgap of IGZO.[20] This result means that the bonding states in the IGZO layer have been changed with the Mg addition. We also deconvoluted the O spectra to inspect the change of bonding states, as shown in Fig. 6. The O 1s peak can be fitted by three nearly Gaussian distributions, respectively, centered at O_I (529.96 ± 0.1 eV), O_{II} (531.55 ± 0.1 eV), and O_{III} (532.7 ± 0.1 eV). O_I is related to the $O_2{}^-$ ion in the lattice surrounded by the Zn, Ga and In atoms in the IGZO compound system. O_{II} is associated with $O_2{}^-$ ions that are in oxygen deficient regions within the matrix of IGZO. O_{III} is usually attributed to the presence of loosely bound oxygen on the surface of the film termed the specific chemisorbed oxygen.[21,22] It can be found there is an increase in O_I and O_{II}, and the ratio of O_{III} is reduced with Mg doping. The obvious increase in the amount of O_{II} shows the oxygen vacancy can be reduced with Mg doping. Moreover, the bonding energy of MgO (393.7 kJ/mole) is higher than ZnO (284.1 kJ/mol) at 298 K.[23] It is hard to break the MgO bond as compared to the ZnO bond. Thus, we think the increase in O_{II} ratio, the MgO_x formation in IGZO and the high bonding energy of MgO bond result in good stability of the IGZO-TFTs during operation. This indicates that Mg doping can enhance the ratio of $O_2{}^-$ ion in the lattice surrounded by the Zn, Ga and In atoms in the IGZO compound system, and increase the ratio of oxygen deficient regions within the matrix of IGZO. However, the ratios of indium, gallium and zinc oxides cannot be convincingly identified at this stage; further investigation is under its way for clarifying the ratios of various oxides. But, we still believe, according to our experimental data, the presence of Mg can change the intrinsic properties of the IGZO thin film and in turn influence the electrical characteristics of IGZO-TFTs.

In this study, the effects of Mg doping on the electrical properties of IGZO-TFTs have been investigated. The TFTs with composite IGZO/Mg-doped IGZO channel depict better electrical performance than the IGZO-TFTs without Mg doping in terms of on/off ratio and S.S.. We measured the output characteristics and also analyzed the contact resistance by TLM. The mobility degradation of Mg-doped IGZO-TFTs is due to the poorer contact resistance between the Mg doped IGZO layer and the Ti electrode, which is supposed to come from the smaller grain size in the Mg-doped IGZO. From the bandgap measurement by the optical experiment, the bandgap can be tailored by the ratio of Mg doping; however, it should be optimized. Mg doping in IGZO can suppress the effect of positive and negative biases effectively. By XPS analysis, it can be observed the composition in the IGZO layer does change with Mg doping. The presence of Mg can change the oxygen bonding states and influence the properties of IGZO layer. Consequently, Mg doping can improve the electrical performance of the IGZO-TFTs and the optimization such as Mg concentration and the thickness of Mg-doped IGZO layer would be studied in the future.

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