IZO Thin Film Transistor-Oriented Trap State UV Analysis Using Random Matrix

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With the popularization of electronic equipment, indium zinc oxide (IZO) thin film transistor (TFT) research has become a hot spot. Due to the excellent characteristics of solution method, solution-processed IZO TFTs have seen wide applications in various fields. However, the study on the trapping state distribution of solution-processed IZO TFTs is not thorough enough, and the current research methods have limitations. Therefore, the ultraviolet (UV) analysis method is introduced for analyzing the trap state distributions. Then, the UV analysis method is optimized using the random matrix. The interface and bulk trap states are extracted, and the feature of trap states is analyzed. Experimental results show that under the proposed method, the bulk trap concentration of IZO TFTs is $10^{18} \sim 10^{19}$ cm$^{-3}$ eV$^{-1}$, and the interface state density is $10^{12} \sim 10^{13}$ cm$^{-2}$ V$^{-1}$. They all change with wavelength. The proposed method is effective, feasible, and easy to implement. The research will make an important contribution to the preparation of high-performance IZO TFTs.

1. Introduction

With the development of mobile electronic equipment and screen display technology, thin film transistor (TFT) has attracted the attention of many researchers. The working voltage of a TFT is determined by its threshold voltage, which is determined by the dielectric gate material. Therefore, the study of TFT should start from the gate dielectric material [1, 2]. TFT is an essential device in liquid crystal display (LCD). Its performance will directly affect the display quality of LCD. Improving the structure, preparation process, and materials can enhance the TFT performance. Therefore, the research on TFT has become an important research direction in the field of display technology.

Compared with silicon-based materials, indium zinc oxide (IZO) has better internal properties. IZO thin film features high mobility and controllable resistivity. It is a promising oxide semiconductor material, so it has been widely used in various research fields [3, 4]. Recently, many scholars have studied IZO TFT. For example, Shur et al. studied an amorphous IZO TFT prepared by atomic layer deposition, which obtained excellent performance [5]. Migliorato et al. examined IZO TFT by controlled sputtering [6]. Schropp et al. investigated the effects of temperature and light on the instability induced by the negative bias of Hf-InZnO deposited by radio frequency (RF) sputtering [7, 8]. Despite these achievements, there are relatively few studies on the defect characteristics of solution-fabricated IZO.

In recent years, with the application expansion, the disadvantages of transistors have become prominent, such as large threshold voltage [9, 10]. TFT involves a multi-layer active stack, and its trap state distribution is very complex [11–13]. Therefore, aiming at the above problems, the defects of solution-treated IZO by photoelectron spectroscopy are studied in this work. The ultraviolet (UV) spectrophotometer measures the light transmittance and trap state distribution to study the optical properties of the solution-fabricated IZO TFTs. Then, to improve the test results of the UV-visible photometer, the research model is optimized based on random matrix theory.
2. Experimental Details of Film and Device

2.1. Preparation of IZO Precursor Solutions. Acetyl acetone (AcAc, Sigma-Aldrich, 99.5%) was mixed with ammonium hydroxide (NH₄OH, 28% NH₃ in water, Sigma-Aldrich, 99.99%) in a ratio of 1.4:1.0, and indium nitrate (In(NO₃)₃·4H₂O, Alfa Aesar, 99.999%) was added to make 0.2 M In₂O₃ solution. Add 3.5 ml of 2-methoxyethanol to the mixture, extract 1.5 ml, and add acetyl acetone and ammonium hydroxide in a ratio of 6:5, using the same substance as above. Stir the precursor solution for 17 h and filter. Mix the two precursors to make the desired material. Let them stand for 24 h.

2.2. IZO Thin Film Preparation. The substrate is 100 nm thick SiO₂. The substrate is rinsed and the substrate is treated by plasma. The coating was rotated on the substrate for 30 seconds at 4300 rpm and preannealed for 5 minutes (80°C). The monolayer films were annealed by rapid thermal annealing at 400°C at a flow rate of 6 SLPM for 25 min. The annealing environment is initialized before treatment.

2.3. Fabrication of IZO TFT. At present, the dielectric gate materials used to study oxide TFTs are mainly from two aspects: high dielectric constant materials and solid electrolyte materials. The gate dielectric material with a high dielectric constant has a large gate capacitance, which can reduce the working voltage of the device. Because of the double-layer effect, the solid electrolyte can form an equivalent high-capacitance double-layer capacitor to improve the capacitance, effectively reducing the working voltage of the device.

Using SiO₂ as gate medium, IZO TFT is fabricated. The IZO channel region was defined as 1000 μm wide and 200 μm long, and 150 nm aluminum source and drain were prepared by thermal evaporation. Figure 1 displays the sectional structure of the IZO TFT.

3. UV Model Design Based on Random Matrix

By using the UV absorption of molecules or ions of substances, the resulting UV-visible spectrum can analyze, determine, and infer the composition, content, and structure of substances. Therefore, UV analysis can be used for quantitative analysis of substances. The characteristics of absorption peaks can also be used for qualitative analysis and simple structure analysis to determine some equilibrium constants and coordination ratios of complexes.

Random matrix theory studies the statistical characteristics of the eigenvalues of huge matrices. The goal is to randomly extract various characteristics of the matrix of entries through probability distributions, traditionally called random matrix combinations. The numerical methods commonly used to calculate eigenvalues are the QR method and the power method (direct and indirect). The QR method is a stable numerical algorithm, and the power method is an iterative algorithm. Random matrix theory has been widely used in physics, statistics, engineering, and other research fields. In particular, by optimizing the UV analysis method with a random matrix, the accuracy of the results can be improved.

Threshold voltage can be given by [1]

\[ V_{th} = V_{fb} + \phi_s - \frac{Q_b + Q_i}{C_{ox}}. \]

(1)

where \( Q_b \) is the fixed bulk charge, which is due to the ionized acceptors in the depletion layer, \( Q_i \) represents the mobile charge density in the IZO film, \( C_{ox} \) is the gate capacitance, and \( \phi_s \) represents the surface potential of the semiconductor. The flat voltage satisfies [2]

\[ V_{fb} = \frac{qN_{ss} + Q_i}{C_{ox}} + \phi_m + \chi_s, \]

(2)

where \( q \) is the electronic charge, \( Q_i \) is the charge of the oxide, \( \phi_m \) is the function of gate metal, and \( \chi_s \) is the electron affinity of IZO [3]. \( V_{FB} \) is an equivalent that describes the charge neutrality in the metal-insulator-semiconductor structure: fixed and mobile charges of insulator, work functions, surface states, space-charge accumulation, and built-in potentials at the interface [4].

\( N_{ss} \) is the density of the oxide/IZO interface charge, which mainly affects the electrical characteristics including the sub-threshold swing value and can be expressed as [5]

\[ N_{ss} = \int_{E_v}^{E_c} D_g (E_c - E) dE, \]

(3)

where \( E_c \) and \( E_v \) are the conduction band edge and the valence band edge, respectively, and \( D_g \) is the density of the oxide/IZO interface trap states. In the thin film transistors, the interface state causes the voltage shift [6, 7]. Combining equations (2) with (3), \( E \) difference increases; then,

\[ \frac{\partial V_{fb}}{\partial E} = \frac{q}{C_{ox}} D_g (E_c - E). \]

(4)

Meanwhile,
\[
Q_b = -q \int_0^{t_d} \left[ \int_{E_v}^{E_{C}} N(t)(E_{C} - E) \right] dE \right] dx,
\]

\[
Q_t = -q \int_0^{t_{ch}} \left[ \int_{E_C}^{\infty} N(E) f(E) dE \right] dx,
\]

where \( N_t \) is the trap density in IZO film and \( f(E) \) is the Fermi–Dirac distribution function. The lower the carrier density is, the closer the density of \( N(E) \) state is to the density at the bottom of the conduction band \([2, 8]\).

\[
t_d = \left( \frac{2\varepsilon_0 \varepsilon_s \phi_b}{qN_{ch}} \right)^{1/2},
\]

where \( \varepsilon_0 \) and \( \varepsilon_s \) are permittivity and relative permittivity, respectively. For IZO, \( \varepsilon_{IZO} = 9 \) \([10]\). \( \phi_b \) is the difference between Fermi level \( E_F \) and intrinsic Fermi level \( E_i \), which can be estimated by 1/2 of band gap \([11, 12]\). The carrier density in the channel \( N_{ch} \) satisfies \([13, 14]\)

\[
N_{ch} = \frac{C_{ox}}{q} \frac{V_{gm}}{qL_{ch}},
\]

where \( V_{gm} \) is the gate voltage, which is identified as the gate voltage at which the drain current increase begins in a transfer curve \([15, 16]\). Divide both sides of equation (1) by the increase of photon energy \( \Delta E \):

\[
\frac{\partial V_{th}}{\partial E} = \frac{\partial V_{fb}}{\partial E} - \frac{\partial Q_b}{\partial E},
\]

Integrate it with equation (4) to get

\[
\frac{\partial V_{th}}{\partial E} = \frac{q}{C_{ox}} \left( D_d (E_C - E) + t_d N_t(E_C - E) \right).
\]

The sub-threshold swing SS \([17, 18]\) is

\[
SS = \frac{kT}{q \log e} \left[ 1 + \frac{q}{C_{ox}} (D_d + t_{ch} N_t) \right].
\]

Combine equation (11) with equation (10) to get

\[
N_t = \frac{C_{ox}}{q(t_{ch} - t_d)} \left( SS \frac{q \log e}{kT} - 1 - \frac{\partial V_{th}}{\partial E} \right),
\]

\[
D_d = \frac{C_{ox}}{q(t_{ch} - t_d)} \left[ (-t_d) \left( SS \frac{q \log e}{kT} - 1 \right) + t_{ch} \frac{\partial V_{th}}{\partial E} \right].
\]

4. Discussion and Results

Related parameters used in this model are listed in Table 1. Integrate with equation (7) and substitute into equations (12) and (13), densities of bulk trap states and interfacial states can be derived. The results of this method are shown in Figures 2 and 3.

From the figures, one can obtain that trap densities can be changed under illumination. This process is related to the reemission and recombination of trapped carriers. With photon absorption supplied, oxygen vacancies can be positively ionized via electron emission. Photoexcited electrons effectively change the charge of defects \([22, 23]\).

From the calculation results, one can gain that obtained \( N_t \) and \( D_d \) are in the order of \( 10^{18} - 10^{19} \text{cm}^{-3} \text{eV}^{-1} \) and \( 10^{12} - 10^{15} \text{cm}^{-2} \text{V}^{-1} \), respectively. The data are higher than

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
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<tbody>
<tr>
<td>( t_{IZO} )</td>
<td>12</td>
<td>nm</td>
</tr>
<tr>
<td>( t_{ox} )</td>
<td>100</td>
<td>nm</td>
</tr>
<tr>
<td>( \varepsilon_{IZO} )</td>
<td>9</td>
<td>—</td>
</tr>
<tr>
<td>( \varepsilon_{ox} )</td>
<td>3.9</td>
<td>—</td>
</tr>
<tr>
<td>( L )</td>
<td>200</td>
<td>( \mu )m</td>
</tr>
<tr>
<td>( W )</td>
<td>1000</td>
<td>( \mu )m</td>
</tr>
</tbody>
</table>

Figure 2: Distributions of bulk trap states.
other processed IZO films [24, 25]. It is perhaps because of the many kinds of solvents in the process, which introduced different defects. Nevertheless, solution deposition offers the possibility of the direct pattersability of transparent oxide semiconductor thin films which can be applied for backplane devices of displays and replace the conventional photolithographic technique [26].

Additionally, it shows that with the increase of wavelength, defect density increased firstly and decreased later, and peaks are around 3.2 eV. As we know, illumination can neutralize the ionized oxygen vacancy defects [27]. So, densities of the defects increased; however, illumination can generate electron-hole pairs as well, which can be trapped by defects. When the concentrations of photon-generated carriers amount to a certain value, it will directly decrease the extracted densities obviously. Besides, the density of trap state changes is in agreement with that of IZO, thus verifying the method’s effectiveness [28].

5. Conclusion

The trap state distribution of IZO TFT largely determines the electrical characteristics and long-term stability of TFT. Therefore, designing a reasonable and reliable trap state analysis method can help analyze the electrical characteristics of IZO TFT and understand the stability mechanism of IZO material by constructing the TFT model. In this paper, a method for extracting trap states of solution-processed indium zinc oxide thin film transistors has been developed. This method is capable of extracting the value of both the bulk and the interface trap states. Also, it is simple, easy to implement, and widely applicable, which offers a more easily comprehensible way to appreciate the influence of defect states on device properties and also a basis for guiding the improvement of TFT fabrication. The research has far-reaching significance for promoting and developing mobile device display technology. Additionally, it is worth mentioning that an equivalent basic understanding of the defects that are responsible for instabilities in TFTs for specific structure systems will be critical before the commercial application in displays or other areas such as flexible electronics can be realized. This area is ripe for more work.

Data Availability

The dataset used in this paper is available from the corresponding author upon request.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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