The Vacancy Pool Model for Amorphous In-Ga-Zn-O Thin-Film Transistors

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Abstract—In this paper, the reaction rate of oxygen vacancy ($V_O$) by the derivatives of threshold voltage ($V_{th}$) in the amorphous indium-gallium-zinc oxide thin-film transistors under light pulses with altering duty ratios is investigated. More importantly, after collecting and analyzing a lot of experimental results, a comprehensive model named $V_O$ pool is proposed. The proposed model can more universally describe the characteristic of $V_O$ reacting to the light and its degradation behavior under various kinds of stress condition.

Index Terms—amorphous indium gallium zinc oxide (a-IGZO), thin-film transistors (TFTs), reaction rate, illumination effect, multiple-pulse illumination, response time, oxygen vacancy.

I. INTRODUCTION

Recently, metal oxide semiconductors have been promised for the next generation of transparent display industry due to many advantages such as high electron mobility, low off current [1], [2], low cost process temperature, and good transmittance. Among metal oxide-based materials, amorphous Indium-Gallium-Zinc-Oxide (a-IGZO) thin-film transistors (TFT) is the most attractive channel material, because the larger mobility than a-Si, better uniformity than LTPS, high on/off ratio, and the highly transmittance over 90% due to its wide band gap (~3 eV) in visible light (400–700 nm), and so on. Owing to these good properties, a-IGZO TFTs open up to new applications such as transparent electronics [3], flexible electronics [4], [5], and photo sensors [6], [7].

Although a-IGZO TFTs have many advantages, the significant electrical instability under bias stress and light illumination is observed. Many papers reported threshold voltage shift ($\Delta V_{th}$) and mobility change after illumination [8]-[13]. The different models were proposed to depict the degradation behavior of TFTs under various stress conditions involving light intensity, temperature, bias stress [14]-[20]. In our previous studies, we proposed a reaction model to describe the different reaction rate of oxygen vacancy ($V_O$) reacting with the light pulses [21]-[24]. Even though all the deterioration behaviors under all kinds of stress conditions are similar, the reaction rates of them are too diverse to be pictured in a unified expression. In this paper, we attempt to propose a representative model to interpret the diverse degradation characteristics of the stressed a-IGZO TFTs.

To verify the proposed model, the broad stress conditions in light intensity, gate bias, light pulse of period, and light pulse of duty cycle are applied to the a-IGZO TFTs. In this study, the devices are subject to the same fabrication process and measurement method, which are described in our previous papers [21]-[25]. Based on the previous research, oxygen vacancies reacting with the light-induced electron hole pairs play the leading role in $\Delta V_{th}$ [8]-[11], [19]. Therefore, the time differential of $\Delta V_{th}$ is employed to investigate the reaction rate of $V_O$. We expect the proposed model to well explain the results and give an insight into the behaviors of $V_O$ in a-IGZO TFTs.

II. THE RESPONSE TO LIGHT PULSES WITH DIFFERENT DUTY RATIOS

A. The reaction rate in cycles of light pulses

The reaction rates in $V_{th}$ can be represented by the derivatives of $V_{th}$ versus time [24]. Fig. 1 overlaps the curves clipped from the dark intervals between light pulses of 20,000 Lux and 1.67 Hz for several cycles. The data plotted in Fig. 1(a) and (b) are with duty ratios of 33% and 83%, respectively. As can be seen, the reaction rates in many cycles are identical, which reconfirms our previous work [24].

![Graph showing the reaction rate in cycles of light pulses](image-url)
For the intervals under light, the rates are depicted by the absolute value of the derivative of $V_{th}$ versus time and plotted in Fig. 2. Here, the negative shift of $V_{th}$ is happened and attributed to the domination of positively charged $V_O$ ($V_O^{2+}$ or $V_O^+$) instead of electron trapping at the a-IGZO/gate insulator (GI) interface [26]. We can see that the reaction rate is relatively large in the first few cycles and converges thereafter, which is also consistent with our previous work [24]. The temporally higher reaction rates in the beginning can averaged out with the convergent ones for the further analysis in the following section.

**B. Leverage of the duty ratio on the reaction rate**

From Fig. 1 and 2, the average reaction rates could be obtained by the sum of peak value in each cycle divided by the number of cycles. The average reaction rates in the parts under and between the light pulses with respect to the duty ratio are plotted in Fig. 3(a) and 3(b), respectively. Besides, the error bar is also plotted to examine the accuracy of the average reaction rate. From figures, the concave upward curves are observed. According to our previous study [24], the observed reaction rate of $V_O$ is strongly related to the time of measurement. As duty ratio is small, the duration of illumination is accordingly short. Thus, only those faster $V_O$ can react adequately and then recover quickly enough to be re-excited again. On the other hand, when duty ratio is high, the dark interval is too short for the slower $V_O$ to recover and then react when the next light pulse comes. For the duty ratios at both ends, the faster $V_O$ dominate the reaction rate, because the slower $V_O$ are excluded from the measurement. In the case of 50% duty ratio, the balanced intervals of light and darkness allow the slower $V_O$ to involve, and thus the slowest reaction rate happens. This phenomenon reveals that the reaction rates of $V_O$ in a-IGZO spread differently.
III. THE PROPOSED MODEL TO DESCRIBE THE REACTION AND DISCUSSION

In our previous research [21]-[24], a fitting formula had been proposed to describe the change of drain current (ΔI_D) under illumination in short and long term. More importantly, with more fitting terms, the accuracy of fitting can be better, which reveals the reaction contained by several reaction rates of Vo [24]. Interestingly, the similar results are reported in the study of the light effect on hydrogenated amorphous silicon (a-Si:H) to represent the various types of defect [27], [28]. Furthermore, K. Winder and Powell et al. reported these defects with dangling-bond, caused ΔVth, are in different energy states and the defect pool model was proposed to interpret the degradation [29]-[31]. However, unlike a-Si TFTs, the repeatability of experimental results is hardly achievable for a-IGZO TFTs. It is highly related to the process of reaction and recovery involving different reaction rate of Vo. With the similarity and discrepancy, a vacancy pool model in a-IGZO is presented by considering all the features we observed.

A. Proposing a vacancy pool model

To provide a more comprehensive impression for the diverse degradation behaviors of a-IGZO under various duration of illumination, a new model named as “vacancy pool” is proposed. The word pool implies that Vo in a-IGZO are so many and various that they can have different reaction rates distributing over a very wide range. The fitting parameters had been well discussed in detail in our previous reports [21]-[24], [32]. We found the number of reacting Vo was dependent on the light intensity. Moreover, the strong correlation between the characteristic time constant Tau and stress time hints the diversity of the reaction rate can be correspondingly observed by the experiments in the time of interest [23], [24]. In each experiment, measurement time is fixed, and ΔVth reflects only a part of Vo in vacancy pool. Those Vo reacting relatively fast are considered as initial state, while those slower Vo have no chance to get involved. To justify the proposed model, we need to give the overall picture of the rate Vo reacting to the light.

B. Picturing the proposed model

Many experimental conditions of light intensity and bias are collected from several references [6], [24], [33]-[38] and our experiment and plotted in Fig. 4. In the gray region of upper right corner, ΔVth is too large to be observed under the strong light intensity and high bias. Using the results from those collected experiments in Fig. 4, ΔVth versus response time are plotted in Fig. 5. The response time is the duration when Vth is affected by Vo. Owing to the time of interest [24], the response time would be observed decisively upon stress time. The wide range of response time from 10 ms to 10,000 s displays the evidence of widely distributing reaction rate for the Vo in the pool. Furthermore, the 100 times variation in ΔVth for the same response time also clearly demonstrates the diversity of vacancy pool. The result suggests the severe degradation caused by those faster Vo should be cautiously considered. Besides, the data out of the measurement limit cannot be included here, but it is believed that there are Vo in the pool can react to the light and bias at other different rates.

Fig. 4. The light intensity versus bias.

Fig. 5. ΔVth versus response time under different stress condition.

IV. CONCLUSION

A comprehensive vacancy pool model is proposed to provide an overall picture for Vo in a-IGZO TFT. The proposed model could universally explain the various degradation behavior under kinds of conditions, including those under light pulses with altering duty ratios. The wide distribution of reaction rate can make difficulty in using a-IGZO TFTs in applications that require stable characteristics under dynamic light ambiance. Therefore, the concept of “vacancy pool” should be kept in mind.

REFERENCES


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