In-line Process Monitoring for Amorphous Oxide Semiconductor TFT Fabrication using Microwave-detected Photoconductivity Decay Technique

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1. Introduction

Amorphous In–Ga–Zn–O (a-IGZO) is a promising material for highly efficient thin-film-transistors (TFTs) in next generation flat panel display since one can obtain higher field effect mobilities over 10 cm²/Vs with a matured film formation technique [1]. It is widely recognized that the performances of a-IGZO TFTs are governed by the electronic properties of the films, which are often modified by their manufacturing process. As compared with conventional channel materials such as amorphous Si, the a-IGZO is extremely sensitive to the manufacturing process of the TFTs, thus, stabilization of the film characteristics is an issue which should be solved to realize the a-IGZO TFTs for practical use.

It has been difficult to presume the performances of the TFTs only from the characteristics of the a-IGZO thin films. In our previous study, it was found that a strong correlation between the TFT mobilities and the peak values of the microwave photoconductivity decay (μ-PCD) for the corresponding a-IGZO thin films [2]–[3]. The decay curve of the μ-PCD consists of at least two kinds of decay components, namely the fast and the slow decay curves. The origin of the latter is attributed to reemission of the electrons captured at the defect-like states just below the conduction band minimum (CBM). Therefore, analyzing the slow decay curves obtained by the μ-PCD measurements could be useful for monitoring the change of the electronic properties during the fabrication process to manage the IGZO-TFT performances.

According to several researchers [4]–[9], the reliability of the IGZO-TFTs is related to defect states below the CBM in the a-IGZO thin films. In particular, during the light-illumination and negative-bias temperature stress (LNBTS), it is considered that the defect-like states are formed, which causes the change of the threshold voltage (Vth) of the TFTs.

In the present study, we made detailed investigation on the slow decay component in the μ-PCD signals from the a-IGZO thin films and correlated with the Vth shift induced during the LNBTS test. We have proposed a practical evaluation parameter “τ2” which can be used as an in-line monitoring tool for the a-IGZO TFT fabrication processes.

2. Interpretation of μ-PCD Signals and Determination of τ2 as an Evaluation Parameter for LNBTS

Generally, in the photoconductivity responses from semiconductors having a decay constant of τ, the density of excess carriers after photoexcitation can be described by the following equation;

\[ n(t) = n_0 \exp(-t/\tau) \]

where \( n_0 \) is the carrier density just after the photoexcitation; \( t \) is the time after the photoexcitation.

Figure 1 shows a typical μ-PCD decay curve of the a-IGZO thin film. The decay curve can be divided into three components; the peak value, and the two kinds of decay including the fast and the slow decay constants, which is different from the decay curves obtained on LTPS thin films [10]. According to our previous study [3], we assumed that the density of the carriers participating in the microwave conductivity obeys the following equation after photoexcitation:

\[ n(t) = n_0[\exp(-t/\tau_f) + \exp(-t/\tau_s)\beta^2] \]

where \( \tau_f \) and \( \tau_s \) are the fast decay and the slow decay time constants, respectively; and \( \beta \) is the stretching exponent. The slow decay was found to be related to the reemission and recombination of trapped carriers from the defect...
states located at 0.1 ~ 0.2 eV. The fact that the slow decay can be described by a stretch exponential \[11\]–\[13\] suggests that the energy level of the defect states is broad and close to the Fermi level of the system.

As described in the previous section, one of the origins of the \(V_{th}\) shift of the IGZO-TFTs during the LNBTS test is the change of the defect-like states just below the CBM in the a-IGZO thin films. This issue is examined by some researchers using a simulation model \[14\], i.e., the influences of the energy levels of the defects \(E_{GD}\) were evaluated by using the model where the donor-like defect-related states were put below the CBM near the back channel of the TFTs. These simulation results indicated that the TFT properties were affected by the localized states, which were observed in the TFT transfer curves by the variation of the hump shoulder depending on the \(E_{GD}\). When the donor-like defect states are located above the Fermi level, the defect-like states are instantly ionized, which results in the hump phenomena in the TFT transfer curves. In the case that the donor-like defects form very shallow states below the CBM, the TFT transfer curves show a parallel shift during the LNBTS tests. On the other hand, the hump phenomena are frequently observed during the LNBTS. The formation of the hump implies that the values of the \(E_{GD}\) are rather deep compared from the defect levels mentioned above. This is the case in the present study. Therefore, we have investigated the slow decay constant of \(\mu\)sec order range not less than \(1\) sec. The slow decay \(2\) corresponds to the slope between \(t_1\) and \(t_2\), as shown in Fig. 1. The value of \(t_2\) is calculated from the slope of the decay curves in the region where the almost exponential decrease is observed and on the order of a few microseconds.

As a result, the following equation is considered:

\[
n(t) = n_0 \exp(-t/\tau_1) + n_1 \exp(-t/\tau_2),
\]

The \(\beta\) value describes the relaxation of the system to equilibrium \[15\]–\[17\]. \(\beta = 1\) is substituted since the slow decay in the \(\mu\)sec range shows good linearity in the semi-log plots.

3. Experimental

3.1 Apparatus of \(\mu\)-PCD

The \(\mu\)-PCD method is a non-destructive, contactless technique that enables characterization of the capture, recombination, and relaxation of laser-excited carriers by observing the temporal response of the microwave reflectivity \[10\]. The apparatus of \(\mu\)-PCD system is shown in Fig. 2. The excess carriers are injected into the films by the laser pulse. The change in the carrier concentration after the excitation is observed by the microwave reflectivity.

In general, the evaluation of thin films is difficult to secure enough \(S/N\) ratio for signal detection since the thickness of the film is very thin like 40 nm and the quality of the film is not as good as that for crystal. To overcome this problem, the differential detection system shown in Fig. 2 is utilized. Two waveguides are equipped with and only the film under the signal waveguide is illuminated. Output from reference waveguide contains noise, while that from signal waveguide contains both signal and noise. By subtracting the both output, we can extract only \(\mu\)-PCD signal. This differential detection system improves the \(S/N\) ratio more than 500 times.

3.2 Sample Preparation

The schematics of the a-IGZO films for \(\mu\)-PCD measurements were shown in Fig. 3(a). The a-IGZO films were deposited on glass substrates by DC sputtering using an InGaZnO\(_4\) target. The thickness of the films is fixed at 40 nm. The film is then annealed at 350°C for 1 h in air. The duration of the annealing was fixed at 60 min otherwise mentioned.

For evaluation of the influence of hydrogen contents in gate insulators (GIs), the following samples were prepared. The schematics of the samples are shown in Fig. 3(b). The 250 nm CVD-SiO\(_x\) layer was deposited on glass substrates. The a-IGZO films were deposited on the glass substrates covered with the SiO\(_x\) layer by DC sputtering with the same conditions mentioned above. The thickness of the film was
The cross-sectional structures of (a) a-IGZO film for \( \mu \)-PCD measurement, (b) a-IGZO film for evaluating influence of a gate insulator (GI) and (c) a-IGZO TFT.

Figure 3(c) schematically shows a cross-sectional structure of the a-IGZO TFTs with a bottom gate structure. The fabrication process of the TFTs is as follows: The 250 nm CVD-SiO\(_x\) layer was used as a GI, which was deposited on a glass substrate with a Mo gate electrode. A-IGZO films with a thickness of 40 nm were deposited on the substrates. The a-IGZO films were photolithographically patterned and the samples were annealed at 350° C for 1 h in air. Then, the source and drain electrodes consisting of Mo were deposited and patterned. The CVD-SiN layer was continuously formed as a passivation layer after deposition of CVD-SiO\(_x\) layer. Finally, the a-IGZO TFTs were annealed at 250° C for 1 h in N\(_2\).

The channel length (L) of the TFT is 20 \( \mu \)m, while the channel width (W) is 210 \( \mu \)m. The measurements of the transfer curves and the values of the \( V_{\text{th}} \) shift (\( \Delta V_{\text{th}} \)) during the LNBTS tests were performed by using a semiconductor parameter analyzer (Keithley 4200-SCS).

The gate voltage (\( V_{\text{gs}} \)) was swept between -30 and 30 V while the drain voltage (\( V_{\text{ds}} \)) is fixed at 10 V. The \( V_{\text{th}} \) is defined as \( V_{\text{ds}} \) when the value of \( I_{\text{th}} \) exceeds 1nA. The LNBTS test is carried out under the following conditions: \( V_{\text{gs}} \) and \( V_{\text{ds}} \) are fixed at -20 and 10 V, respectively, and a substrate temperature is set at 60°C. The luminance during the LNBTS test is 25,000 cd/m\(^2\) (nit). In the LNBTS test, the \( \Delta V_{\text{th}} \) is defined as; \( \Delta V_{\text{th}} = V_{\text{th},7200s} - V_{\text{th}, \text{initial}} \), where \( V_{\text{th},7200s} \) is the \( V_{\text{th}} \) value after 7200 sec and \( V_{\text{th}, \text{initial}} \) is the initial \( V_{\text{th}} \).

4. Results

The values of the \( V_{\text{th}} \) shift and the \( \tau_2 \) are plotted in Fig. 4 as a function of oxygen partial pressure during the a-IGZO deposition. This graph shows excellent correlation between the \( \tau_2 \) estimated from the slow decay and the valued of the \( V_{\text{th}} \) shift under the LNBTS test, the latter of which is strongly influenced by the parameters of sputtering conditions. The \( V_{\text{th}} \) shift becomes smaller with increasing the partial pressure of oxygen during the deposition of the a-IGZO. When the partial pressure of oxygen is 10% and more, the value of the \( V_{\text{th}} \) shift is saturated, and the value of \( V_{\text{th}} \) shift becomes less than 1 V. With decreasing the oxygen partial pressure during the a-IGZO sputtering, the carrier concentration in the films increases due to an increase of the donor-like defect [18]. Therefore, it is reasonable thought that the value of \( \tau_2 \) has correlation in the oxygen partial pressure. The good correlation between the \( \Delta V_{\text{th}} \) and the \( \tau_2 \) value suggests that the donor-like defects introduced in the films affect the TFT stability. Deduced from the result of Fig. 4, the most desirable sputtering conditions for acquiring the best stability with our sputtering apparatus could be at around 10% oxygen addition.

Secondly, the effects of annealing were evaluated. Figure 5 shows the \( \mu \)-PCD decay curves from the a-IGZO thin films with various annealing duration. In the experiments, the annealing temperature was fixed at 350°C (in air) and the annealing time was varied between 5 and 120 min. After annealing at least 5 min, the decay curves were drastically changed compared with that obtained before annealing. Af-
Fig. 6  $V_{th}$ shift by LNBTS and $\tau_2$ values in terms of annealing time at 350$^\circ$C in air.

Fig. 7  Relationship between $V_{th}$ shift by LNBTS and $\tau_2$ values.

After annealing for 30 min, the slow decay curve is slightly moved downward, and then that of 60 min did the same way. The slow decay curve of 120 min annealing sample was almost the same as that for 60 min.

The values of the $V_{th}$ shift and the $\tau_2$ are summarized in Fig. 6. Both the $\Delta V_{th}$ and the $\tau_2$ after 60 min-annealing become the smallest than the others, therefore the annealing at 60 min could be the best conditions. After annealing at 120 min, the $V_{th}$ shift and the $\tau_2$ values were slightly increased. This result should be attributed to the formation of two kinds of defect states during the annealing. It has been reported that the desorption of oxygen and zinc from the a-IGZO films occurred depending on the annealing temperature and time [18], [19]. According to the results of thermal desorption spectrometry for the a-IGZO thin films, desorption of $O_2$, and $H_2O$ started at temperatures lower than 250$^\circ$C. On the other hand, desorption of Zn atoms occurred at temperatures higher than 300$^\circ$C. Therefore, it is considered that the characteristics of the a-IGZO films determined as a result of competition between oxygen and zinc-related defect formation.

Figure 7 summarized the relationship obtained by plotting these data with the value of the $V_{th}$ shift for horizontal axis and the values of the $\tau_2$ for vertical axis. This result shows a linear relationship between $\tau_2$ obtained from decay curves shown and the value of $V_{th}$ shift from TFT fabrication. These examples are one of the critical steps in R&D stage of IGZO-TFT development.

The quality of the GI films and the passivation films often affects the performances of actual TFTs. Thus, correlation with the measurement results using the $\mu$-PCD method and the characteristics of TFT was considered, and the possibility of characteristic prediction was examined. It should be noted that, at the time of mass-production, the production yield is secured by monitoring difference of $\mu$-PCD data.

The influences of the GI film quality on the performance of the IGZO-TFTs were examined by analyzing the $\mu$-PCD signals. The process flow is shown in Fig. 8. The GI films consisting of SiO$_x$ with different properties were deposited by PE-CVD, and the stacked layers were fabricated by deposition of the a-IGZO thin films on them. The amount of hydrogen contained in the GI films is changed according to the CVD conditions and summarized in Table 1, in which the hydrogen contents in the GI films are estimated by elastic recoil detection analysis (ERDA).

Indeed, dependence of the GI film quality on the electronic structures of the a-IGZO thin films was pointed out based on the analysis by isothermal capacitance tran-

<table>
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<tr>
<th></th>
<th>SiH$_4$ flow (sccm)</th>
<th>CVD Pressure (Pa)</th>
<th>CVD Temperature ($^\circ$C)</th>
<th>Hydrogen contents in GI film</th>
</tr>
</thead>
<tbody>
<tr>
<td>GI-1</td>
<td>4</td>
<td>200</td>
<td>320</td>
<td>1.2at%</td>
</tr>
<tr>
<td>GI-2</td>
<td>4</td>
<td>200</td>
<td>230</td>
<td>3.1at%</td>
</tr>
<tr>
<td>GI-3</td>
<td>4</td>
<td>200</td>
<td>150</td>
<td>4.4at%</td>
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<tr>
<td>GI-4</td>
<td>10</td>
<td>200</td>
<td>320</td>
<td>3.1at%</td>
</tr>
<tr>
<td>GI-5</td>
<td>4</td>
<td>80</td>
<td>320</td>
<td>1.9at%</td>
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sient spectroscopy (ICTS) using metal oxide semiconductor (MOS) diodes with the same fabrication process and the structure as those for the actual a-IGZO TFTs [20]. It was proposed that diffusion of H and OH from the a-IGZO to the GI film causes the formation of the defect states in the a-IGZO films.

The $\mu$-PCD responses of the a-IGZO thin films formed on the various GI films are shown in Fig. 9. It is shown that the decay curve of GI-3 is different from the other decay curves. This suggests that the film quality of a-IGZO was changed in response to the influence of GI-3. The TFT characteristic actually deteriorated remarkably, as shown in Fig. 10, therefore the $\Delta V_{th}$ was not able to be determined.

Figure 11 shows the correlation between $\Delta V_{th}$ of TFTs with a-IGZO thin films under LNBTS test, and the slow decay $\tau_2$ measured by $\mu$-PCD.

5. Discussion

Here, we discuss the origin of the $\mu$-PCD responses. It is understood that the fast decay is reported due to recombination center as shown in Fig. 12 [3]. On the other hand, the origin of the slow decay $\tau_2$ is related to the phenomena that the laser-excited carriers are trapped at the localized states (i.e. defect-like condition) just below the CBM of a-IGZO thin film and that the carriers are de-trapped into conduction band by thermal emission. According to H. J. Kim [21], incorporated hydrogen makes the defects just below the CBM of a-IGZO thin film, which leads to $\Delta V_{th}$ shift under LNBTS. Furthermore, $V_{th}$ shift under LNBTS test often makes hump phenomena, which can be explained by the introduction of defect formed just below the CBM [14], [22], [23].

As for ZnO, many researchers report on the density of states near the CBM by DLTS [24], [25]. There are some defect-like states observed, which are named as $E1$, $E2$, $E3$, and so on. Especially, it has turned out that $E3$ with a comparatively deep level state (0.3 eV below the CBM) is related to hydrogen [26]. Recent research suggests that the similar center is also involved in the a-IGZO thin films [19]. Since the slow decay constant of the $\mu$-PCD curves corresponds to emission from shallow localized states, it could be concluded that the correlation between the value of $\tau_2$ and the $V_{th}$ shift under LNBTS test is obtained. However, other effects such as relationship with $E2$, originated from Zn deficiency/oxygen rich defects, are not excluded at this stage.

As shown in this study it is clear that monitoring electronic structure just below the CBM of oxide film is really effective to evaluate the reliability of oxide TFTs under the
We have investigated the \( \mu\text{-}PCD \) method, which is a promising method for in-line process monitoring for the IGZO-TFTs fabrication.

6. Mapping Measurements

In the previous study [3], one can extract the optimized conditions which give the reasonable TFT mobility by measuring the peak values of the decay curves. The peak value mapping on a whole substrate will help to understand the uniformity of the characteristics of the a-IGZO film. For example, it is known that the characteristics do not become uniform by oxygen addition in the process gas for a large glass substrate especially in the case of reactive sputtering method.

Figure 13 shows a mapping measurement result for a \( 440 \times 375 \text{ mm}^2 \) substrate. The mapping measurements provide useful information on distribution of the film thickness, mobility, and light stability. By checking the mapping of \( \mu\text{-}PCD \), it is possible to optimize the distribution of various properties. As shown in Fig. 14, \( \mu\text{-}PCD \) systems corresponding to various substrate sizes are already available for measurement of the amorphous oxide semiconductors.

7. Summary

We have investigated the \( \mu\text{-}PCD \) responses from the (a-IGZO thin films. The time constant extracted by the slopes of the slow part of the reflectivity signals were compared with various TFT performances, where the influence of the sputtering conditions, as well as the influences of the GIs and annealing conditions on the quality of a-IGZO thin films were evaluated. By using the \( \mu\text{-}PCD \) method, the characteristic of a-IGZO thin film is able to be judged, and the results show reasonable correlation with the characteristic of TFTs. Since slow decay curve has a correlation with shallow localized states, the \( \mu\text{-}PCD \) is found to be useful as the technique especially for evaluating the LNBTS characteristic of TFTs.

The mapping technique within a large substrate is also useful as a non-destructive process monitoring method for oxide semiconductors sensitive to TFT process. The \( \mu\text{-}PCD \) method is a promising method for in-line process monitoring for the IGZO-TFTs fabrication.

References


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