Study on the Lateral Carrier Diffusion and Source-Drain Series Resistance in Self-Aligned Top-Gate Coplanar InGaZnO Thin-Film Transistors

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We investigated the lateral distribution of the equilibrium carrier concentration ($n_0$) along the channel and the effects of channel length ($L$) on the source-drain series resistance ($R_{\text{ext}}$) in the top-gate self-aligned (TG-SA) coplanar structure amorphous indium-gallium-zinc oxide (a-IGZO) thin-film transistors (TFTs). The lateral distribution of $n_0$ across the channel was extracted using the paired gate-to-source voltage ($V_{\text{GS}}$)-based transmission line method and the temperature-dependent transfer characteristics obtained from the TFTs with different $L$s. $n_0$ abruptly decreased with an increase in the distance from the channel edge near the source/drain junctions; however, much smaller gradient of $n_0$ was observed in the region near the middle of the channel. The effect of $L$ on the $R_{\text{ext}}$ in the TG-SA coplanar a-IGZO TFT was investigated by applying the drain current-conductance method to the TFTs with various $L$s. The increase of $R_{\text{ext}}$ was clearly observed with an increase in $L$ especially at low $V_{\text{GS}}$s, which was possibly attributed to the enhanced carrier diffusion near the source/drain junctions due to the larger gradient of the carrier concentration in the longer channel devices. Because the lateral carrier diffusion and the relatively high $R_{\text{ext}}$ are the critical issues in the TG-SA coplanar structure-based oxide TFTs, the results in this work are expected to be useful in further improving the electrical performance and uniformity of the TG-SA coplanar structure oxide TFTs.

In the last decade, amorphous indium-gallium-zinc oxide (a-IGZO) thin-film transistors (TFTs) have attracted considerable attention due to their advantages such as a high field-effect mobility ($\mu_{\text{FE}}$), a low off-current, and a small subthreshold swing1-4. In addition, the a-IGZO TFTs are fabricated at low temperatures (below 300 °C) with a good uniformity over large areas6-10. These excellent properties make the a-IGZO TFT a promising candidate for the backplane element of active-matrix liquid-crystal displays and active-matrix organic light-emitting diode (AMOLED) displays11,12. Up to now, the a-IGZO TFTs have been fabricated with several structures including a bottom-gate etch stopper structure, a bottom-gate back-channel-etch structure, and a top-gate self-aligned (TG-SA) coplanar structure7. Among them, the TG-SA coplanar structure has many advantages compared with bottom-gate structures, such as smaller parasitic capacitance, better channel length scalability, and better process controllability13,14. Owing to these merits, the TG-SA coplanar structure a-IGZO TFT is desirable especially for high-resolution AMOLED applications15,16. However, despite such advantages, there still remain some issues to be solved in TG-SA coplanar a-IGZO TFTs. One of them is the threshold voltage ($V_{\text{th}}$) dependence on the channel length of the device17-19. In the TG-SA coplanar a-IGZO TFTs, the source/drain extension regions are n$^+$-doped in order to lower the source/drain series resistance ($R_{\text{ext}}$). The high-density free carriers in the source/drain extension regions diffuse into the IGZO channel layer during the subsequent annealing process, which increases the carrier concentration of the channel region and shifts $V_{\text{th}}$ to the negative direction especially in the short channel

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devices. Therefore, the study on the lateral carrier diffusion and $R_{\text{ext}}$ is very important in the TG-SA coplanar a-IGZO TFTs to further improve the electrical performance and uniformity of the devices. In this work, we extracted the lateral distribution of the carrier concentration in the TG-SA coplanar a-IGZO TFTs by using the paired gate-to-source voltage ($V_{\text{GS}}$)-based transmission line method (TLM) and temperature-dependent transfer characteristics data obtained from the TFTs with various channel lengths. Furthermore, we investigated the effects of channel length on the $R_{\text{ext}}$ of the TG-SA coplanar a-IGZO TFT using the drain current-conductance method (DCCM).

**Results and Discussion**

Figure 1(a) depicts a cross-sectional schematic of the fabricated TG-SA coplanar a-IGZO TFTs, where the fabrication process of the TFTs is introduced in the Methods Section. Figure 1(b) shows the schematic carrier concentration plot along the channel between the source and drain in the TG-SA coplanar a-IGZO TFTs. Near the source and drain junctions, the carriers diffuse from the n$^+$/doped source/drain extension regions to the channel region. Solid lines represent the equilibrium carrier concentration ($n_0$) and the dotted lines represent the $V_{\text{GS}}$-induced carrier concentration at two different $V_{\text{GS}}$s ($V_{\text{GS1}} > V_{\text{GS2}}$). As can be observed in Fig. 1(b), there are two distinct regions: one is the region where $V_{\text{GS}}$-induced carrier concentration is higher than $n_0$ and the other is the region where $n_0$ is higher than the $V_{\text{GS}}$-induced carrier concentration. The conductivity in the former region is controlled by $V_{\text{GS}}$, thus this region can be considered as an effective channel region. Because the effective channel ends where the $V_{\text{GS}}$-induced carrier concentration is equal to $n_0$, the effective channel length ($L_{\text{eff}}$) increases with an increase in $V_{\text{GS}}$. $\Delta L$ is defined as the difference between the drawn channel length ($L$) and $L_{\text{eff}}$ ($\Delta L = L - L_{\text{eff}}$). $R_{\text{ext}}$ is the source-drain series resistance associated with all the regions outside the effective channel region.

Figure 1. (a) Cross-sectional schematic of the fabricated TG-SA coplanar a-IGZO TFTs. (b) Schematic carrier concentration plot along the channel between the source and drain in the TG-SA coplanar a-IGZO TFTs.
Figure 2(a) depicts the transfer curves of the TG-SA coplanar a-IGZO TFTs with various $L_s$ ($W/L = 4 \, \mu m/3, 4.5, 6, 10, 20 \, \mu m$) measured in the linear region ($V_{DS} = 0.1 \, V$). $V_{th}$ was determined by the intercept of the extrapolated curve with the $V_{GS}$ axis in the linear-scale transfer characteristics. Figure 2(b) displays the $V_{th}$s obtained from the fabricated TG-SA coplanar a-IGZO TFTs with different $L_s$. Here, $V_{th}$ was determined by the intercept of the extrapolated curve with the $V_{GS}$ axis in the linear-scale transfer characteristics.

To extract the lateral carrier concentration distribution near the source/drain junctions in the TG-SA coplanar a-IGZO TFTs, the paired $V_{GS}$-based TLM was employed. In the TG-SA coplanar TFTs, the total resistance between source and drain electrodes measured in the linear region ($R_{tot}$) can be expressed using the following equation:

$$R_{tot} = \frac{V_{DS}}{I_D} = \frac{L - \Delta L}{W \cdot \mu_{FEI} \cdot C_i \cdot (V_{GS} - V_{th} - V_{DS}/2)} + R_{ext}$$

(1)
where $\mu_{FEi}$ is the intrinsic field-effect mobility and $C_i$ is the gate insulator capacitance per unit area, respectively. Figure 3(a) shows the $R_{tot}$-L plot measured from the TFTs with different $L$ ($L = 6, 12, 20 \mu m$) at a given $V_{DS}$ of 0.1 V for various $V_{GS}$s ($=1$ to 5 V with 0.2 V steps). Figure 3(b) is the enlarged image of the encircled area in Fig. 3(a). In the paired $V_{GS}$-based TLM, $\Delta L$ and $R_{ext}$ at a certain $V_{GS}$ are extracted from the intersection of two straight lines obtained at two closely separated voltages ($V_{GS} \pm \Delta V_{GS}$) where $\Delta V_{GS}$ is 0.2 V in this work. Figure 4(a,b) show the $\Delta L$ and the width-normalized $R_{ext}$ ($W \cdot R_{ext}$) extracted as a function of $V_{GS}$ by using the paired $V_{GS}$-based TLM. $\Delta L$ and $R_{ext}$ are largely modulated by $V_{GS}$ which confirms the presence of the unintentionally doped regions formed by the lateral carrier diffusion from the n$^+$-doped source/drain extension regions in the fabricated TG-SA coplanar a-IGZO TFTs. The results of Fig. 4(a) and the definition of $L_{eff}$ in Fig. 1(b) allow the extraction of the lateral carrier concentration distribution in the unintentionally doped regions near the source/drain junctions. In the TFT, the $V_{GS}$-induced channel carrier concentration ($n(V_{GS})$) can be calculated using the following equation:

$$n(V_{GS}) = C_i \cdot (V_{GS} - V_{th}) / q \cdot t$$

(2)

where $q$ and $t$ are the electronic charge and channel thickness, respectively. As explained in Fig. 1(b), $L_{eff}$ ($=L - \Delta L$) ends where $n$ is equal to $n_i$ in the TG-SA coplanar a-IGZO TFTs, therefore, $\Delta L$ is uniquely determined at a specific value of $V_{GS}$ by the results of Fig. 4(a). Because both $n$ and $\Delta L$ are obtained as a function of
by matching the \( \Delta L/2 \) and \( n \) values calculated at every \( V_{GS} \). Figure 5 displays the lateral distribution of \( n_0 \) in the unintentionally doped regions near the source/drain junctions in the fabricated TG-SA coplanar TFT with \( L = 20 \mu m \) (\( V_{th} = 1.06 \) V). It shows that \( n_0 \) abruptly decreases from \( 1.5 \times 10^{18} \) cm\(^{-3} \) to \( 8.2 \times 10^{16} \) cm\(^{-3} \) as the distance from the edge of the channel (\( \Delta L/2 \)) increases from 0.16 \( \mu m \) to 1.63 \( \mu m \).

The lateral carrier concentration distribution in the channel region far from the source/drain junctions can be extracted using the temperature-dependent transfer characteristics data obtained from the TFTs with different \( L \). Figure 6(a–e) show the temperature-dependent linear-mode transfer curves (\( V_{DS} = 0.1 \) V) of the TFTs with various \( L \)s (\( L = 3, 4, 6, 12, 20 \) \( \mu m \)) measured at low \( V_{GS} \)s and Fig. 7(a–e) depict the Arrhenius plots obtained from the results in Fig. 6(a–e). In the disordered semiconductor-based TFTs, the energy distance between the Fermi level and conduction band edge in the flat-band condition (\( E_{aFB} = E_C - E_F \)) has been successfully extracted using the temperature-dependent transfer characteristics according to the procedure described in the previous works\(^{22-24} \).

Figure 8 shows the evolution of \( E_{aFB} \) and \( n_0 \) extracted from the TFTs with different \( L \)s using the experimental results in Figs 6 and 7. \( n_0 \) was calculated from

\[
n_0 = n_{IGZO} \cdot \exp \left( -\frac{E_{aFB}}{kT} \right)
\]

where \( n_{IGZO} \) is the effective density of states at the conduction band edge in IGZO at room temperature (\( =5.0 \times 10^{18} \) cm\(^{-3} \))\(^{25} \) and \( k \) is the Boltzmann constant, respectively. Figure 8 shows that \( E_{aFB} \) increases and \( n_0 \)

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Figure 4. (a) \( \Delta L \) and (b) width-normalized \( R_{ext} \cdot W \cdot R_{ext} \) extracted as a function of \( V_{GS} \) by using the paired \( V_{GS} \)-based TLM.
decreases, with an increase in \( L \). These results are consistent with the positive shift of \( V_{th} \) with an increase in \( L \) observed in Fig. 2. In the TG-SA coplanar TFT, \( n_0 \) is different depending on the distance from the edge of the channel due to the carrier diffusion from the n⁺-doped source/drain extension regions. Considering that the carrier diffusion takes place from both source and drain regions, \( n_0 \) is believed to have the lowest value in the middle of the channel. Because the \( V_{th} \) of the laterally non-uniformly doped TFT is determined by the lowest carrier concentration in the channel region, the calculated \( n_0 \) in Fig. 8 based on the results in Figs 6 and 7 can be assumed to be the \( n_0 \) in the middle of the channel in each TFT with different \( L \). These results allow us to extract the values of \( n_0 \) as a function of the distance from the edge of the channel in the channel region far from the source/drain junctions. Figure 9 shows the lateral distribution of \( n_0 \) in the whole channel region of the fabricated TG-SA coplanar TFT with \( L = 20 \mu m \).

Because the relatively higher \( R_{ext} \) has been considered as a weakness of the TG-SA coplanar structure than the bottom gate structures in a-IGZO TFTs, the extraction of the exact values of \( R_{ext} \) is very important in the TG-SA coplanar a-IGZO TFTs to further improve the electrical performance of the devices. In this work, we investigated the effects of \( L \) on the \( R_{ext} \) of the TG-SA coplanar a-IGZO TFT for the first time using the DCCM. As given in Fig. 4(b), the \( R_{ext} \) of the TG-SA coplanar a-IGZO TFT can be extracted not only by the DCCM but by the paired \( V_{GS} \)-based TLM. However, because the \( R_{ext} \)s are assumed to be the same in all TFTs with different \( L \)s in the paired \( V_{GS} \)-based TLM, the extracted \( R_{ext} \) from the paired \( V_{GS} \)-based TLM is the averaged one of the TFTs with different \( L \)s. The DCCM was developed to extract the \( V_{GS} \)-induced source and drain series resistance (\( R_{source} \) and \( R_{Drain} \)) in the highly-doped-drain metal-oxide-semiconductor field-effect transistors (MOSFETs). It can extract the \( R_{source} \) and \( R_{Drain} \) separately by using the \( I_{DS} \)s and output conductances (\( G_{DS} \))s measured in the forward and reverse operation modes in the linear operation regime, respectively. DCCM is to form four independent equations to solve \( R_{source} \)s, \( R_{Drain} \)s, \( \mu_{FE,\text{fwd}} \), and \( \mu_{FE,\text{rev}} \) where \( \mu_{FE,\text{fwd}} \) and \( \mu_{FE,\text{rev}} \) are \( \mu_{FG} \)s for the forward and reverse mode operations, respectively. Equations (4) and (5) are the two of the four equations which are for the forward mode operation and equations (6) and (7) are those for the reverse mode operation.

\[
I_D = \mu_{FE,\text{fwd}} \cdot \frac{C_i \cdot W}{L_{eff}} \cdot \left( V_{GS} - V_{th} - \frac{1}{2} V_{DS} \right) \cdot V_{DS}
\]

where \( V_{GS} = V_{GS} - I_D \cdot R_{source} \) and \( V_{DS} = V_{DS} - I_D \cdot (R_{source} + R_{Drain}) \).

\[
G_D = \frac{\partial I_D}{\partial V_{DS}} = \mu_{FE,\text{fwd}} \cdot \frac{C_i \cdot W}{L_{eff}} \cdot \left( V_{GS} - V_{th} - \frac{1}{2} V_{DS} \right) \cdot \frac{\partial V_{DS}}{\partial V_{DS}} + \left( \frac{\partial V_{GS}}{\partial V_{DS}} \right) \cdot \frac{\partial V_{DS}}{\partial V_{DS}} \cdot V_{DS}
\]

where \( \frac{\partial V_{GS}}{\partial V_{DS}} = - G_D \cdot R_{source} \) and \( \frac{\partial V_{DS}}{\partial V_{DS}} = 1 - G_D \cdot (R_{source} + R_{Drain}) \).

\[
I_D = \mu_{FE,\text{rev}} \cdot \frac{C_i \cdot W}{L_{eff}} \cdot \left( V_{GS} - V_{th} - \frac{1}{2} V_{DS} \right) \cdot V_{DS}
\]

where \( V_{GS} = V_{GS} - I_D \cdot R_{source} \) and \( V_{DS} = V_{DS} - I_D \cdot (R_{source} + R_{Drain}) \).

Figure 5. Lateral distribution of \( n_0 \) in the unintentionally doped regions near the source/drain junctions in the fabricated TG-SA coplanar TFT with \( L = 20 \mu m \).
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where $V_{GS}$ and $V_{DS}$ are the gate-source and drain-source voltages, respectively, and $G_D$ is the drain conductance. The DCCM requires only a single device for the extraction of $R_{ext}$, and the W·$R_{ext}$ can be extracted as a function of $V_{OV}$ in the fabricated TG-SA coplanar a-IGZO TFT with different $L$s, where $V_{OV}$ represents $V_{GS} - V_{th}$. For comparison, the W·$R_{ext}$ extracted using the paired method is shown in Figure 10.

Figure 6. Temperature-dependent linear-mode transfer curves ($V_{DS} = 0.1 \text{ V}$) measured from the TFTs with different $L$ s ((a) 3 μm, (b) 4 μm, (c) 6 μm, (d) 12 μm, and (e) 20 μm).
VGS-based TLM in Fig. 4(b) is also included as an inset. The results in Fig. 10 clearly shows that the $R_{ext}$ is increased with an increase in $L$ especially at low $V_{GSs}$. Considering that the $R_{ext}$ at low $V_{GSs}$ is dominated by the unintentionally doped channel regions formed by the lateral carrier diffusion from the n+–doped source/drain extension regions near the source/drain junctions, the higher $R_{ext}$ in the longer channel TFTs is believed to be mainly caused by the enhanced carrier diffusion (large $\Delta L$) due to the larger gradient of the carrier concentration in the longer channel devices.

Figure 7. Arrhenius plots obtained from the results in Fig. 6 for TFTs with different $L$s ((a) 3 μm, (b) 4 μm, (c) 6 μm, (d) 12 μm, and (e) 20 μm).
Conclusion

In this work, we examined the lateral distribution of $n_0$ across the channel and the effects of $L$ on the $R_{\text{ext}}$ in the TG-SA coplanar a-IGZO TFTs. The lateral distribution of $n_0$ across the channel was extracted using the paired $V_{\text{GS}}$-based TLM near the source/drain junctions and using the temperature-dependent transfer characteristics data measured from the TFTs with different $L$s near the middle of the channel, respectively. $n_0$ abruptly decreased from $1.5 \times 10^{18}$ cm$^{-3}$ to $8.2 \times 10^{16}$ cm$^{-3}$ at room temperature as the distance from the edge of the channel ($\Delta L/2$) increases from 0.16 $\mu$m to 1.63 $\mu$m in the fabricated TG-SA coplanar TFT with $L = 20 \mu$m. However, much smaller gradient of $n_0$ was observed in the channel region far from the source/drain junctions. To examine the effect of $L$ on the $R_{\text{ext}}$ in the TG-SA coplanar a-IGZO TFTs, the DCCM was employed. The $R_{\text{ext}}$s were extracted from the TFTs with different $L$s, which clearly showed that $R_{\text{ext}}$ increased with an increase in $L$ especially at low $V_{\text{GS}}$. The observed phenomenon was possibly attributed to the enhanced carrier diffusion (large $\Delta L$) near the source/drain junctions in the long channel devices.
A SiO\textsubscript{2} layer was deposited by plasma-enhanced chemical vapor deposition as a gate insulator followed by the sequential deposition of a gate metal. After deposition and patterning of the gate electrode and the gate insulator, the source/drain extension regions were self-aligned to the gate and are n\textsuperscript{+}-doped by being exposed to the plasma during the dry-etching process. Interlayer dielectrics were deposited and patterned for source/drain contact holes. Then, the metal layer was sputtered and patterned to form the source/drain electrodes. The TFTs were passivated by a SiO\textsubscript{2} passivation layer. Finally, the devices were thermally annealed to achieve the stable and uniform electrical performances.

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**Figure 10.** \( W \cdot R_{\text{ext}} = (W \cdot R_{\text{ext,5}} + R_{\text{ext,LD}}) \) extracted as a function of \( V_{\text{GS}} \) in the fabricated TG-SA coplanar a-IGZO TFT with different \( L_s \). For comparison, \( W \cdot R_{\text{ext}} \) extracted using the paired \( V_{\text{GS}} \)-based TLM in Fig. 4(b) is included as an inset.
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**Author Contributions**

S.Y., H.J.K., I.T.C., J.N., P.S.Y., S.W.L. and H.I.K. designed this work. I.T.C. and J.N. fabricated the devices, and S.Y.H., H.J.K., D.H.K. and H.Y.J. measured the electrical characteristics of the devices and performed the analysis. S.H.S., K.S.P., S.Y. and I.K. provided a theoretical advice for proceeding experiments. S.Y.H. and H.I.K. wrote the manuscript. The project was supervised by H.I.K.

**Additional Information**

**Competing Interests:** The authors declare no competing interests.

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