Modelling localized charge-injection region of the p-channel low-temperature polycrystalline silicon thin-film transistor

KwangHyun Choia, YoungHa Sohna, GeumJu Moona, YongSang Kimb, Jae-Hong Jeonc and KeeChan Parka

aDepartment of Electronics Engineering, Konkuk University, Seoul, Korea; bDepartment of Electrical & Electronic Engineering, Sungkyunkwan University, Suwon, Korea; cSchool of Electronics, Telecommunications and Computer Engineering, Korea Aerospace University, Goyang, Korea

ABSTRACT
The low-temperature polycrystalline silicon (LTPS) thin-film transistor (TFT) is the optimal device for the backplane of the organic light-emitting diode display. At the end the p-channel LTPS TFT fabrication, a charge-injection stress with a strong negative drain bias and a positive gate bias are applied to reduce the off-current by injecting electrons into the gate insulator near the drain. In this study, the charge density and the length of the charge-injection region in the gate insulator were estimated by comparing the measured TFT characteristics with the simulation models with various charge-injection lengths and charge densities. It was found that the effective length of the charge-injection region was 0.96 µm and the charge density was $-3 \times 10^{12}$/cm$^2$ for the 2-µm-channel-length device when $V_{GS}$ was $+20$ V and $V_{DS}$ was $-10$ V under the charge-injection stress condition. It was also found, based on the analysis of the electric field distribution under the bias stress condition, that the charge density and the length of the charge-injection region were invariant against the channel length variation. Therefore, the measured TFT characteristics also accorded closely with the simulation models for different channel lengths, such as 4 and 10 µm, when the same characteristic values of the charge-injection region were employed.

1. Introduction
The application of the active-matrix organic light-emitting diode (AMOLED) display was recently expanded to include smartphones, TVs, and wearable devices owing to its high image quality, lightweight, and free-form factor. The low-temperature polycrystalline silicon (LTPS) thin-film transistor (TFT) is the optimal device for OLED driving in the backplane of small and medium-sized AMOLED displays owing to its high carrier mobility and stability. The off-state drain current of the LTPS TFT, however, often exceeds 1 pA, and it further increases tens or hundreds of times when the reverse gate-to-drain bias becomes as large as the gate-induced drain leakage (GIDL) current that prevails [1,2]. To suppress the large GIDL current of the LTPS TFT exclusively for the p-channel device, charge-injection bias stress is applied to some critical switching devices in the pixel after completing the fabrication. Under the bias stress condition, a large positive gate bias and a negative drain bias are applied to the p-channel TFT. As a result, a number of electrons are injected into the gate insulator near the drain, and they relieve the electric field near the drain during the off-state [3]. It was found that the localized charge in the gate insulator does not only reduce the GIDL current but also changes the threshold voltage ($V_T$) change and the GIDL current reduction using the TCAD (technology computer-aided design) model. The estimation results accord quite well with the measurement results of the 4- and 10-µm-channel-length devices even though they were extracted from the characteristics of a 2-µm-channel-length device.

2. Experiments
The devices that were used in the experiments were top-gated p-channel LTPS TFTs with a 50-nm-thick polycrystalline silicon (poly-Si) active layer and a 100-nm-thick silicon dioxide gate insulator layer. The poly-Si film was crystallized through XeCl excimer laser annealing. The bias conditions of the charge-injection stress were
Figure 1. Measured transfer characteristics in forward mode before and after the charge-injection stress application: (a) $L = 2\, \mu m$; (b) $L = 4\, \mu m$; and (c) $L = 10\, \mu m$.

$V_{GS} = +20\, V$ and $V_{DS} = -10\, V$. The charge-injection stress was applied for 10 min. The transfer characteristics of the TFTs were measured before and after the stress application. The TFT characteristics were measured in two modes: the forward and reverse modes. In the reverse mode, the source and drain of the TFT were exchanged compared with the stress situation.

Figure 1 shows the forward-mode measurement results, and Figure 2 shows the reverse-mode results for the 2, 4, and 10 $\mu m$ channel lengths. The dashed line represents the pre-stress characteristics, and the solid line represents the post-stress characteristics. In the forward-mode measurement results in Figure 1, the off-currents of the pre-stress devices increase with increasing $V_{GS}$ beyond 0 V, regardless of the channel length, but the off-currents of the post-stress devices are maintained at below 0.2 pA for up to $+10\, V$ $V_{GS}$, regardless of the channel length. In the reverse-mode results in Figure 2, however, the pre- and post-stress off-currents are almost the same, increasing nearly exponentially as $V_{GS}$ increases beyond 0 V. In addition to the off-current reduction, which is the original purpose of the application of charge-injection stress, it should be noted that a positive $V_T$ shift appears after the stress application in both the forward and reverse modes of the 2-$\mu m$ device. Positive $V_T$ shifts are also observed for the 4- and 10-$\mu m$ devices, but they are small.

3. TCAD analysis

Figure 3 schematically shows the state of the LTPS TFT after the stress application. Electrons are injected into the gate insulator near the drain under the bias stress condition, and they remain in the gate insulator after the bias stress application. The trapped electrons reduce the electric field near the drain when a positive $V_{GS}$ is applied, which suppresses the off-current increase with increasing $V_{GS}$ in the forward mode. In the reverse mode, however, the off-current is not suppressed because the electron injection region is switched to the source side. Accordingly, the off-current does not change before and after the charge-injection stress application in the reverse mode.

The areal density of the trapped electrons may not be constant along the source-to-drain direction, but it is almost impossible and useless to find the exact areal charge distribution because it may be critically affected by the random distribution of the grain boundary protrusions. It is thus assumed that the trapped charge density...
in the charge-injection region is constant, and that there is no trapped charge outside the said region. It is also assumed, for simplicity, that the trapped electrons are located at the interface between the poly-Si and the SiO$_2$ gate insulator, as shown in Figure 4. There are thus two parameters that should be determined: the areal density of the trapped electrons and the length of the charge-injection region indicated in Figure 3. It is thought that these two parameters can be found by fitting the off-current change and the $V_T$ shift between the pre- and post-stress characteristics using the TCAD device model (Table 1).

Silvaco’s ATLAS TCAD tool was used for the analysis. First, the trap state parameters of the poly-Si film and the Si-SiO$_2$ interface region were determined by fitting the TFT characteristics measured before the stress application. The characteristic length of the lateral dopant diffusion at the source/drain junctions was also optimized to
fit the measured TFT characteristics of different channel lengths with a single set of parameter values. To exclude the effect of the random distribution of the grain boundaries in the poly-Si film on the TFT characteristics, the poly-Si layer was not divided into in-grain and grain boundary regions, but the trap state density was assumed to be constant throughout the whole poly-Si layer. As the effect of the Si-SiO$_2$ interface traps, however, could not be ignored in fitting the measured characteristics, the interface region was separately considered. The whole set of trap state parameters of the poly-Si film and the interface region were extracted using the data shown in Table 3. These values were used in the equation below in the TCAD simulation of the TFT model [4].

\[ g(E) = g_{TA}(E) + g_{TD}(E) + g_{GA}(E) + g_{GD}(E), \]

where \( g_{TA}(E) \): density of the acceptor-like tail states in the upper half of the bandgap; \( g_{TD}(E) \): density of the donor-like tail states in the lower half of the bandgap; \( g_{GA}(E) \): density of the donor-like deep states; and \( g_{GD}(E) \): density of the donor-like deep states.

To fit the transfer characteristics measured after the charge-injection stress with the TCAD device model, only a localized oxide charge \( Q_f \) was added at the interface, as shown in Figure 4. The length of the charge-injection \( (L_{CI}) \) and the fixed charge density \( (Q_f) \) at that region were extracted using the data shown in Table 3. Here, \( Q_f \) is expressed by the number of electrons per unit area. First, the transfer characteristics of the TCAD model for various \( L_{CI} \) and \( Q_f \) values were investigated. The \( L_{CI} \) values were varied from 0.5 to 1.1 \( \mu \)m, at 0.2 \( \mu \)m increments. The \( Q_f \) values were also varied from 0 to \(-5 \times 10^{12}/\text{cm}^2\), at \(-1 \times 10^{12}/\text{cm}^2\) increments. The initial state of \( Q_f \) before the stress application was assumed to be zero. Then it was found that only the shaded conditions in Table 3 exhibited off-current suppression, like the measurement results obtained after the stress application. Table 3 shows how close the \( \Delta V_T \) shift values of the TCAD models \( (\Delta V_{T,model}) \) are to the measured \( \Delta V_T \) shift value \( (\Delta V_{T,\text{measure}}) \) for the 2-\( \mu \)m-channel-length device. In this analysis, the \( \Delta V_T \) values were extracted using the constant drain current method [5]. In the transfer characteristics shown in Figure 1(a), 50 nA was chosen as the threshold drain current reference \( (I_T) \), and the \( V_{GS} \) value for \( I_T = 50 \) nA was determined to be \( V_T \). It was expected that the minimum value of \( |\Delta V_{T,\text{measure}} - \Delta V_{T,model}| \) might appear between \( L_{CI} = 0.90 \mu \)m and \( L_{CI} = 1.1 \mu \)m for \( Q_f = -3 \times 10^{12}/\text{cm}^2 \). \( L_{CI} \) was thus varied at 0.02 \( \mu \)m increments, and it was found that \( |\Delta V_{T,\text{measure}} - \Delta V_{T,model}| \) had the minimum value when \( L_{CI} \) was 0.96 \( \mu \)m. A \( Q_f \) other than \(-3 \times 10^{12}/\text{cm}^2 \) was not considered because an \( L_{CI} \) range for off-current suppression did not exist for a \( Q_f \) smaller than \(-3 \times 10^{12}/\text{cm}^2 \), or was very small for a \( Q_f \) larger than \(-3 \times 10^{12}/\text{cm}^2 \).

Based on the data in Table 3, it was concluded that \( Q_f = -3 \times 10^{12}/\text{cm}^2 \) and \( L_{CI} = 0.96 \mu \)m were the optimum approximations of the charge-injection region. To confirm the validity of the extraction method that was used, cases of devices with other channel lengths (4 and 10 \( \mu \)m) were investigated. Figure 5 shows the electric

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**Table 1.** Device parameters used in TCAD simulation.

| Device parameters | Symbol (units) | Value |
|-------------------|---------------|-------|
| Channel length    | \( L \) \( (\mu \text{m}) \) | 2, 4, 10 |
| Channel width     | \( W \) \( (\mu \text{m}) \) | 1     |
| Gate oxide thickness | \( t_{ox} \) \( (\text{nm}) \) | 100   |
| Poly-Si thickness | \( t_{Si} \) \( (\text{nm}) \) | 50    |
| Source and drain dopant density | \( N_{A} \) \( (\text{cm}^{-3}) \) | 1 × 10^{20} |
| Characteristic length of lateral dopant diffusion | \( \text{char} \) \( (\mu \text{m}) \) | 0.175 |

**Table 2.** Poly-Si trap state parameters used in TCAD simulation.

| Poly-Si trap state parameters | Symbol (units) | Poly-Si | Si-SiO$_2$ interface |
|------------------------------|---------------|---------|---------------------|
| Density of the acceptor-like tail states | \( N_{TA} \) \( (\text{cm}^{-3} \text{eV}^{-1}) \) | \( 1.6 \times 10^{20} \) | \( 8 \times 10^{20} \) |
| Density of the donor-like tail states | \( N_{TD} \) \( (\text{cm}^{-3} \text{eV}^{-1}) \) | \( 1.04 \times 10^{20} \) | \( 5.2 \times 10^{20} \) |
| Characteristic decay energy of the acceptor-like tail states | \( W_{TA} \) \( (\text{eV}) \) | 0.03 | 0.04 |
| Characteristic decay energy of the donor-like tail states | \( W_{TD} \) \( (\text{eV}) \) | 0.03 | 0.04 |
| Density of the acceptor-like Gaussian states | \( N_{GA} \) \( (\text{cm}^{-3} \text{eV}^{-1}) \) | \( 2.2 \times 10^{17} \) | \( 2.2 \times 10^{10} \) |
| Density of the donor-like Gaussian states | \( N_{GD} \) \( (\text{cm}^{-3} \text{eV}^{-1}) \) | \( 2.2 \times 10^{17} \) | \( 2.2 \times 10^{10} \) |
| Peak energy of the Gaussian distribution of the acceptor-like deep states | \( E_{GA} \) \( (\text{eV}) \) | 0.36 | 0.36 |
| Peak energy of the Gaussian distribution of the donor-like deep states | \( E_{GD} \) \( (\text{eV}) \) | 0.36 | 0.36 |
| Characteristic decay energy of the acceptor-like Gaussian states | \( W_{GA} \) \( (\text{eV}) \) | 0.035 | 0.035 |
| Characteristic decay energy of the donor-like Gaussian states | \( W_{GD} \) \( (\text{eV}) \) | 0.055 | 0.055 |

**Table 3.** Difference between \( \Delta V_{T,\text{measure}} \) (1.10 V) and \( \Delta V_{T,model} \) of the \( L = 2-\mu \text{m} \) device for various charge-injection length \( (L_{CI}) \) and fixed oxide charge \( (Q_f) \) values.

| \( Q_f \) \( (/\text{cm}^2) \) | 0.5 | 0.7 | 0.9 | 0.96 | 1.1 |
|-----------------|-----|-----|-----|------|-----|
| \( L_{CI} \) \( (\mu \text{m}) \) | 1.10 V | 1.10 V | 1.10 V | 1.10 V | - |
| \(-1 \times 10^{12} \) | 1.10 V | 0.98 V | 0.86 V | 0.30 V | - |
| \(-2 \times 10^{12} \) | 1.08 V | 0.91 V | 0.60 V | - | -0.33 V |
| \(-3 \times 10^{12} \) | 1.05 V | 0.81 V | 0.42 V | 0.06 V | -0.90 V |
| \(-4 \times 10^{12} \) | 1.01 V | 0.72 V | 0.29 V | - | -1.33 V |
| \(-5 \times 10^{12} \) | 0.93 V | 0.64 V | 0.11 V | - | -1.60 V |
field profiles at the Si–SiO$_2$ interface under the charge-injection stress condition. It is clearly shown that the electric field profiles are the same near the drain junction, regardless of the channel length. Accordingly, the number of electrons and the length of the charge-injection region should be the same for devices with longer channel length values.

Figure 6 compares the transfer characteristics before and after the charge-injection stress application of the proposed LTPS TFT model with $Q_f = -3 \times 10^{12}/\text{cm}^2$ and $L_{CI} = 0.96 \mu\text{m}$ with the measurement results in forward mode. The channel lengths of the devices are 2, 4, and 10 $\mu\text{m}$, respectively. The dashed lines are the measured transfer characteristics, and the solid lines are the transfer characteristics of the TCAD models. The black lines represent the pre-stress characteristics, and the red lines represent the post-stress characteristics. The off-currents after the charge-injection stress application are consistently suppressed both in the measured transfer characteristics and in the TCAD model characteristics,
Figure 7. Comparison of the measurement results and TCAD models in reverse mode: (a) $L = 2\mu m$; (b) $L = 4\mu m$; and (c) $L = 10\mu m$.

regardless of the channel length. It is also shown that the TCAD models with the same $Q_f$ and $L_{CI}$ values exhibit a very small $V_T$ shift for long-channel-length devices, like the measurement results. This is because the effect of the trapped charge near the drain decreases as the distance between the charge-injection region and the source-to-channel barrier increases. Figure 7 shows that the transfer characteristics of the TCAD model in reverse mode are also in good accord with the $V_T$ shift and GIDL current increase trend of the measured characteristics.

4. Conclusion

Charge-injection stress application in the $p$-channel LTPS TFT is widely employed to suppress the GIDL current. The number of electrons in the charge-injection region, however, and the length of the said region have never been reported. Two-dimensional (2D) TCAD simulation was used to find an approximate model of the charge-injection region in the gate insulator. The GIDL current decrease and $V_T$ shift of a 2-μm-channel-length device were investigated for various $Q_f$ and $L_{CI}$ values, and it was concluded that $Q_f = -3 \times 10^{12}/\text{cm}^2$ and $L_{CI} = 0.96\mu m$ were the optimum values when the stress conditions were $V_{GS} = +20\ V$ and $V_{DS} = -10\ V$. The proposed method can be used to model the charge-injection region for different stress conditions. The validity of the extracted $Q_f$ and $L_{CI}$ values was also confirmed by applying such values to other devices with a longer channel length value (4 and 10 μm).

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Notes on contributors

KwangHyun Choi received his B.S. degree in nano-science and mechanical engineering from Konkuk University Glocal Campus in 2016. He is presently an M.S. candidate in Konkuk University, Seoul. His research is focused on the analysis of the display panel structure and simulation of the LTPS TFT characteristics.
YoungHa Sohn received his B.S. and M.S. degrees in electronics engineering from Konkuk University in 2015 and 2017, respectively. His main interests are LTPS TFT characterization, the pixel compensation circuit of the OLED display, and the driving circuit of the display panel.

GeumJu Moon received his B.S. and M.S. degrees in electronics engineering from Konkuk University in 2015 and 2017, respectively. His research interests are the analysis of the TFT characteristics and power devices like IGBT.

YongSang Kim received his B.S., M.S., and Ph.D. degrees in electrical engineering from Seoul National University, Seoul, South Korea in 1988, 1990, and 1994, respectively. He was a professor in Myongji University from 1995 to 2013, and has been a professor in Sungkyunkwan University since 2013. His research interests are organic-transistor-based biosensors, organic solar cells, oxide TFTs, and solution processing technologies for organic electronic devices.

Jae-Hong Jeon received his B.S., M.S., and Ph.D. degrees in electrical engineering in 1995, 1997, and 2001, respectively, from Seoul National University, Seoul, South Korea. He worked as a senior engineer for Samsung Electronics from 2001 to 2005. From 2005 onwards, he has been a professor in Korea Aerospace University. His research areas include device performance characterization and display panel design using TFTs.

KeeChan Park received his B.S., M.S., and Ph.D. degrees in electrical engineering in 1997, 1999, and 2003, respectively, from Seoul National University, Seoul, South Korea. He worked as a senior engineer for Samsung Electronics from 2003 to 2007. From 2007 onwards, he has been a professor in Konkuk University. His research areas include the display panel design, circuit integration using TFTs, and TFT characterization.

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