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Correlation between Ti source/drain contact and performance of InGaZnO-based thin film transistors

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Ti contact properties and their electrical contribution to an amorphous InGaZnO (a-IGZO) semiconductor-based thin film transistor (TFT) were investigated in terms of chemical, structural, and electrical considerations. TFT device parameters were quantitatively studied by a transmission line method. By comparing various a-IGZO TFT parameters with those of different Ag and Ti source/drain electrodes, Ti S/D contact with an a-IGZO channel was found to lead to a negative shift in VT (ΔV 0.52 V). This resulted in higher saturation mobility (8.48 cm2/Vs) of a-IGZO TFTS due to effective interfacial reaction between Ti and an a-IGZO semiconducting layer. Based on transmission electron microcopy, x-ray photoelectron depth profile analyses, and numerical calculation of TFT parameters, we suggest a possible Ti contact mechanism on semiconducting a-IGZO channel layers for TFTs. © 2013 American Institute of Physics. [http://dx.doi.org/10.1063/1.4790357]

During the last few decades, amorphous indium-gallium-zinc-oxide (a-IGZO) semiconductor-based thin film transistors (TFTs) have gained attention as candidates to substitute for conventional amorphous Si:H TFTs in active matrix liquid crystal displays and organic light emitting diodes. The a-IGZO TFTs are excellent performers and allow low temperature processes.1–3 Proper selection of source and drain (S/D) contact materials is very important for high performance a-IGZO TFTs because gate bias-induced current values, field effect mobility, and switching properties are critically affected by the contact properties of S/D electrodes.4–7 For this reason, titanium (Ti) and molybdenum (Mo) have been widely employed in academic and industry research groups as S/D electrodes for a-IGZO TFTs.8,9 Considering the work function of a-IGZO (~4.5 eV), Ti (4.3 eV), and Mo (4.7 eV) metals are quite reasonable as S/D electrodes. Ti or Mo contact on a-IGZO leads to a negligible Schottky barrier height between S/D electrodes and the a-IGZO semiconducting layer.10 Kim et al. recently reported the carrier transport mechanism of Ti contact with a-IGZO in terms of specific contact resistivity.11 They reported that Ti contact on conductive IGZO layers with high carrier concentration (1.3 × 1019 cm−3) produced high performance Ohmic contact with a specific contact resistivity as low as 2.85 × 10−5 Ω cm2. Although they suggested a possible Ti ohmic contact mechanism, some issues related to the effects of Ti/a-IGZO on a-IGZO TFT device performance still remain.

In normal n-type a-IGZO TFT devices that operate with on voltage (VON) around VGS ≈ 0 V and on-to-off current ratio (Ion/off) of ~1010, the carrier concentration of a-IGZO semiconducting layers is not as high as >~1019 cm−3 (generally ~1017 cm−3).1 With those semiconducting layers, the a-IGZO TFTs cannot operate in normal switching operations due to high off current values.12 For comparison, current-voltage curves with a normal a-IGZO semiconductor layer used in practical TFT devices are shown in Fig. 1(a). It is imperative to investigate the Ti metal contact properties between Ti metal and a-IGZO semiconducting layers and their influence on TFT device performance as S/D electrodes.

FIG. 1. (a) I-V curves resulting from a 50-nm-thick a-IGZO-based semiconducting layer with Ti contacts as a function of different Ti pad spacing (10, 15, 20, 25, 30, 35, and 40 μm), calculated by circular transmission length method. A 50-nm-thick a-IGZO-based semiconducting layer was prepared through an identical TFT process. (b) Cross sectional illustration of a-IGZO TFT with bottom gate and top contact structure.

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In this letter, we concatenate Ti metal contact properties with their electrical contribution in low carrier concentration \( a \)-IGZO semiconductor-based TFTs. TFT device parameters, such as field-effect mobility at saturation region \( (\mu_{\text{SAT}}) \), subthreshold swing (SS), threshold voltage \( (V_T) \), and effective contact resistivity \( (r_{\text{Ceff}}) \), were quantitatively studied. By comparing TFT parameters of \( a \)-IGZO TFTs with different Ag and Ti S/D electrodes, we found that IGZO TFT performance was closely related to lower resistance metal contact. This influenced lower \( r_{\text{Ceff}} \) and \( R_{\text{S/D}} \) values in the vicinity of S/D electrodes. Based on transmission electron microscopy (TEM), x-ray photoelectron (XPS) depth profile analysis, and numerical calculations of TFT parameters, a possible Ti contact mechanism for TFTs on semiconducting IGZO channel layers was suggested.

\( a \)-IGZO TFTs with conventional bottom-gate and top S/D contact structures were fabricated. As shown in Fig. 1(b), an \( a \)-IGZO layer was thoroughly coated onto the SiO\(_2\) dielectric layer to avoid gate over-rapping dependent series resistance behavior. Heavily doped Si (\( \sim 10^{-4} \) \( \Omega \) cm) and thermal-grown 100-nm-thick SiO\(_2\) were used as the gate electrode and dielectric layer. A 50-nm-thick \( a \)-IGZO semiconducting layer was deposited by a conventional radio-frequency (RF) magnetron sputtering system using IGZO (\( \text{In}_2\text{O}_3: \text{ZnO:Ga}_2\text{O}_3 = 1:1:1\) mol) target material at a constant RF power density of 2.2 W/cm\(^2\), working pressure of 2 mTorr, and O\(_2/\)Ar gas flow ratio of 0.015. After deposition, \( a \)-IGZO semiconducting layers were thermally annealed at 300°C for 1 h under atmospheric ambient. Then, 50-nm-thick Ti S/D electrodes were deposited by thermal evaporation and patterned by a conventional photolithographic lift-off method. To compare S/D contact effects on the electrical contribution in TFT devices, highly conductive (\( 4.72 \times 10^{-6} \) \( \Omega \) cm) 50 nm thick reference Ag S/D electrodes were employed with the same evaporation apparatus. During sputtering and thermal evaporation, the substrate temperature was held at less than 50°C. The resistivity of Ti and Ag metal S/D was measured by Hall measurement equipment with van der Pauw configuration (HL5500PC, Accent Optical Technology). The S/D series resistance \( (R_{\text{S/D}}) \), effective contact resistivity \( (r_{\text{Ceff}}) \), and effective transfer length \( (L_p) \) of \( a \)-IGZO TFTs were confirmed by a well-known transmission line method (TLM) that uses photolithographic lift-off patterning. All device characterizations in this experiment were analyzed by a customized probe station (HP4145B) system in a light tight box. Structural and chemical properties were characterized by high-resolution transmission electron microscopy (HRTEM: JEOL JEM2100F) and X-ray photoelectron spectroscopy (XPS: Thermo Scientific) depth profiles, respectively.

XPS depth profile and HRTEM examinations were performed to correlate the electrical and interfacial reactions between Ti and \( a \)-IGZO. Figure 2(a) shows core O1s and Ti2p level spectra of XPS depth profiles obtained from the Ti/a-IGZO interface and \( a \)-IGZO semiconducting layer regions in TFT devices. Unlike with \( a \)-IGZO semiconducting regions, core O1s level spectra in the vicinity of the Ti/a-IGZO interface exhibited additional binding energies of 531.56 eV corresponding to oxygen vacancy states. This additional binding energy indicates oxygen deficient states of \( a \)-IGZO at the region of interfaces.\(^{13}\) In general, oxygen vacancies in the IGZO matrix act as donors, so the formation of oxygen deficient IGZO regions could increase carrier concentration. The core Ti2p level spectra obtained from the Ti S/D and Ti/a-IGZO interface regions also showed different chemical states. The Ti 2p core level peak obtained from the Ti electrode layer showed a binding energy of 453.98 eV, which indicated a complete Ti metal layer.\(^{14}\) However, the Ti 2p core level peak at the Ti/a-IGZO interface showed multiplicity of intermediate Ti oxidation states (TiO\(_x\)). These phenomena in chemical shifts at the Ti/a-IGZO interfacial region were entirely different from the chemical states at the Ag/a-IGZO region. As shown in Fig. 2(b), any chemical shifts at the vicinity of Ag/a-IGZO interface were observed after evaporation of Ag S/D contacts indicating that there is no oxygen vacancies generation by Ag S/D contact. As expected from the XPS profiles in Fig. 2(a), the cross-sectional HRTEM image clearly demonstrated the existence of a very thin TiO\(_x\) interfacial layer between Ti S/D and \( a \)-IGZO semiconducting layers in Fig. 2(c). Rough interface and bright contrast at the interface implies that an interfacial reaction occurred during a Ti metal evaporation.
process. The formation of interfacial TiOx layers can be further explained by formation enthalpies (ΔHf,form), as previously reported for Ti/AlZnO contact.15 Because the formation enthalpies of Ti2O3 (ΔHf,form = −1520.9 kJ/mol), Ti2O5 (ΔHf,form = −2046.9 kJ/mol), Ti3O5 (ΔHf,form = −2459.4 kJ/mol), and TiO2 (ΔHf,form = −944.0 kJ/mol) are much lower than those of In2O3 (ΔHf,form = −925.8 kJ/mol), Ga2O3 (ΔHf,form = −3565.0 kJ/mol), Ga2O3 (ΔHf,form = −1089.1 kJ/mol), and ZnO (ΔHf,form = −350.5 kJ/mol), the formation of TiOx at the interfacial region between Ti and IGZO layers by oxygen out-diffusion from IGZO is reasonable. Kim et al. proposed a similar Ti/IGZO mechanism based on formation enthalpy. They explained that the lower TiOx enthalpy values could result in significant out-diffusion of In, Ga, and Zn at the Ti/IGZO contact region.11

Figures 3(a) and 3(b) show electrical transfer curves of a-IGZO TFTs with reference Ag and Ti S/D electrodes without a post-annealing process after S/D deposition. To identify the electrical contribution of Ti contact in the devices, Ag and Ti S/D electrodes were prepared on identical α-IGZO semiconducting layers. Field effect mobility at the saturation region (μSAT) and SS values were extracted from transfer curves by the following equations:16

\[ I_{DS} = \frac{C_{ox}W}{2L} (V_{GS} - V_T)^2, \quad (V_{DS} = 10.1 \text{ V}) \]  

(1)

and

\[ SS = \frac{\partial V_{GS}}{\partial (\log I_{DS})}, \]  

(2)

where \( I_{DS} \) is drain current, \( C_{ox} \) is capacitance per unit area, \( V_{GS} \) is gate voltage, and \( V_T \) is the threshold voltage that induced a current value of \( W/L \times nA \) at 10.1 \( V_{DS} \). The detailed performance of TFTs for both S/D electrodes is summarized in Table I. The transfer curves of TFTs with Ti S/D electrodes exhibited similar behavior to those of TFTs with Ag S/D electrodes even though Ti S/D has a fairly high electrical resistivity (1.66 \( \times \) \( 10^{-4} \) Ω cm) compared to Ag S/D (4.72 \( \times \) \( 10^{-6} \) Ω cm). The \( \mu_{SAT} \) values of a-IGZO with Ag and Ti S/D electrodes were found to be 4.54 \( \times \) \( 10^{10} \) and 4.66 \( \times \) \( 10^{10} \), respectively. However, the a-IGZO TFT with Ti S/D exhibited a slightly negative shifted \( V_T \) (−Δ 0.52 V) value compared to that of the TFT with Ag S/D electrodes (3.98 V). In general, negative \( V_T \) shifts for n-type TFTs are believed to be associated with the relatively large carrier concentration of a-IGZO.10 In this experiment, a-IGZO layer thickness and process conditions were identically confined. Therefore, the negative shift in \( V_T \) can be interpreted as an increased carrier concentration in the a-IGZO semiconducting layer that resulted due to TiOx formation at the interface. In addition, the a-IGZO TFT with Ti S/D showed a higher \( \mu_{SAT} \) value (8.48 cm²/Vs) than the a-IGZO TFT with Ag S/D electrodes (7.12 cm²/Vs). Lee et al. recently reported that thermionic/field emission current is dominant under large \( V_{DS} \) bias conditions (\( V_{DS} > 10.1 \) V in our device).18 With our a-IGZO semiconducting layer, carrier concentration was found to be approximately 6 \( \times \) \( 10^{16} \) cm⁻³. Assuming that the carrier concentration of the a-IGZO semiconducting layer is around \( \sim 10^{17} \) cm⁻³, current flow at \( V_{DS} \) around 10.1 V should be governed by thermionic emission rather than thermionic/field emission, as shown in Fig. 3(c). Therefore, this enhanced

![FIG. 3. Transfer characteristics of a-IGZO-based thin film transistors with evaporation-deposited (a) Ag and (d) Ti S/D electrodes. Saturation mobility (\( \mu_{SAT} \)) values were obtained at \( V_{DS} \) of 10.1 V. (c) \( E_{\text{ad}} \) and \( kT \) as functions of doping density of a-IGZO semiconducting layer.](image-url)

**TABLE I. Comparative table of device performance for amorphous IGZO TFTs with Ag (4.72 \( \times \) \( 10^{-6} \) Ω cm) and Ti (1.66 \( \times \) \( 10^{-4} \) Ω cm) source/drain electrodes including saturation mobility (\( \mu_{SAT} \)), SS, off current value (Ioff), on current value (Ion), and on-to-off current ratio (Ion/Ioff), respectively.**

<table>
<thead>
<tr>
<th>S/D materials</th>
<th>Ag</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho ) (Ω cm)</td>
<td>4.72 ( \times ) ( 10^{-6} )</td>
<td>1.66 ( \times ) ( 10^{-4} )</td>
</tr>
<tr>
<td>( \mu_{SAT} ) (cm²/Vs)</td>
<td>7.12</td>
<td>8.48</td>
</tr>
<tr>
<td>SS (V/decade)</td>
<td>0.88</td>
<td>0.87</td>
</tr>
<tr>
<td>Ioff (A)</td>
<td>1.50 ( \times ) ( 10^{-13} )</td>
<td>1.46 ( \times ) ( 10^{-13} )</td>
</tr>
<tr>
<td>Ion (A)</td>
<td>6.81 ( \times ) ( 10^{-3} )</td>
<td>6.82 ( \times ) ( 10^{-3} )</td>
</tr>
<tr>
<td>Ion/Ioff</td>
<td>4.54 ( \times ) ( 10^{19} )</td>
<td>4.66 ( \times ) ( 10^{19} )</td>
</tr>
<tr>
<td>( V_T ) (V)</td>
<td>3.98</td>
<td>3.46</td>
</tr>
</tbody>
</table>
\(E_{00} = \frac{qh}{4\pi} \sqrt{\frac{N}{K_s m_{\text{tun}}^*}} = 1.86 \times 10^{-11} \sqrt{\frac{N}{K_s m_{\text{tun}}^*/m}} \text{[eV]},\)

where \(q\) is electron charge, \(h\) is Planck's constant \((6.626 \times 10^{-34} \text{ J s})\), \(N\) is doping density, \(K_s\) is the dielectric constant of \(a\)-IGZO semiconductors \((10.2)\), \(m_{\text{tun}}^*\) is the tunneling effective mass and \(m\) is electron mass. The formation of TiO\(_x\) interfacial layers retains oxygen vacancies at the surface of the \(a\)-IGZO channel layer. Because of this, the carrier concentration of \(a\)-IGZO channel layers could increase after interfacial reactions. We believe that the \(E_{00}\) value increased for this interfacial layer and the current flow mechanism changed from thermionic to thermionic/field emission.

To quantitatively investigate the effects of Ti S/D contact on TFT device parameters, source and drain series resistance \((R_{SD})\), effective contact resistivity \((r_{Ceff})\), and effective transfer length \((L_T)\) were calculated by the TLM.\(^{16}\) Different TFT channel lengths were set at 5, 10, 15, 20, 25, 30, 35, and 40 \(\mu\text{m}\). A global gate electrode was used to minimize the gate dependent \(R_{SD}\) behavior because small gate overlap to source (or drain) electrode can cause large \(R_{SD}\). Figures 4(a) and 4(b) show total TFT ON resistance \((R_T)\) for both \(a\)-IGZO TFTs with respect to TFT channel length for different \(V_{GS}\). Figures 4(c) and 4(d) exhibit \(V_{GS}\) dependent electrical parameters of \(a\)-IGZO TFTs with reference \(Ag\) and Ti S/D electrodes. \(R_T\) is expressed by following equation:\(^{16}\)
VDS
RS
LT
rCeff
2RSD
is
total
series
resistance
and
rch
is
channel
resistance
per
channel
length,
which
is
defined
by
slope
in
RT
versus
source-to-drain
distance.
The
LT,
rCeff,
and
contact
resistivity
(RC)
values
for
a-IGZO
with
both
Ag
and
Ti
S/D
electrodes
were
calculated
by
the
following
approximations:
\[
R_T = \frac{V_{DS}}{I_{DS}} = r_{ch}L + 2R_{S/D},
\]
(4)

where
2RSD
is
total
(series
+ drain)
resistance
and
rch
is
channel
resistance
per
channel
length,
which
is
defined
by
slope
in
RT
versus
source-to-drain
distance.
The
LT,
rCeff,
and
contact
resistivity
(RC)
values
for
a-IGZO
with
both
Ag
and
Ti
S/D
electrodes
were
calculated
by
the
following
approximations:
\[
L_T = \frac{R_{S/D}}{r_{C_{eff}}},
\]
(5)

\[
r_{C_{eff}} = \frac{W}{r_{ch}}L_T^2 + \frac{W}{r_{ch}}R_{S/D}^2,
\]
(6)

\[
R_C = R_{S/D}L_TW.
\]
(7)

Both
rCeff
and
RSD
values
for
a-IGZO
TFTs
with
reference
Ag
and
Ti
S/D
electrodes
dramatically
decreased
with
increased
VGS
within
a
measured
range.
However,
the
a-IGZO
TFT
with
Ti
S/D
electrodes
exhibited
lower
RC,
rCeff,
and
RSD
values
(1.65 \times 10^{-2} \Omega \text{ cm}^2, 8.71 \times 10^{-3} \Omega \text{ cm}^2,
and
507 \Omega )
than
the
a-IGZO
TFT
with
reference
Ag
S/D
electrodes
(4.57 \times 10^{-2} \Omega \text{ cm}^2, 2.29 \times 10^{-2} \Omega \text{ cm}^2,
and
858 \Omega )
at
VGS
= 24 \text{ V},
in
spite
of
the
high
resistivity
of
Ti
metal.
Furthermore,
the
a-IGZO
TFT
with
Ti
S/D
electrodes
had
smaller
LT
values
than
the
TFT
with
Ag
S/D
electrodes,
regardless
of
VGS.
It
is
well
known
that
LT
increases
with
the
thickness
of
the
semiconducting
layer,
bulk
density-of-states,
and
S/D
contact
resistance.

This
work
was
mainly
supported
by
the
Samsung
Mobile
Displays
Research
Center
Program
and
was
partially
supported
by
the
Industrial
Core
Technology
Development
Programs
of
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