Ti/Cu bilayer electrodes for SiN$_x$-passivated Hf–In–Zn–O thin film transistors: Device performance and contact resistance


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Ti/Cu bilayer electrodes for SiN$_x$-passivated Hf–In–Zn–O thin film transistors: Device performance and contact resistance

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In this study, we examine the possibility of using Ti/Cu bilayer as source/drain electrodes for SiN$_x$-passivated Hf–In–Zn–O (HIZO) thin film transistors by comparing their electrical properties with devices that use Mo electrodes. The Mo devices operate in depletion mode with a higher field effect mobility, while the Ti/Cu devices exhibit an improved subthreshold swing and operate in enhancement mode. Transmission electron microscopy characterization reveals the formation of an amorphous TiO$_x$ layer at the Ti/HIZO interface, which is suggested to be responsible for the disparate device characteristics in terms of contact resistance and threshold delay. © 2010 American Institute of Physics. [doi:10.1063/1.3505151]

Oxide semiconductors such as ZnO, GaInZnO (GIZO), or HfInZnO (HIZO) are currently attracting much attention owing to their high potential for application as thin film transistors (TFTs).1–4 Their high field effect mobility (>5 cm$^2$/V s) makes oxide-based TFTs promising switching elements for large area, high resolution active matrix liquid crystal display (AMLCD) products. In a previous article, we reported that in HIZO TFTs using Mo electrodes, SiN$_x$ passivation is more advantageous in terms of mass production because via holes can be etched faster in SiN$_x$ than in SiO$_x$.5,6 However, the SiN$_x$-passivated devices exhibited poorer switching characteristics such as inferior subthreshold swing or negative threshold voltage ($V_T$), despite a high field effect mobility resulting from the incorporation of hydrogen into the underlying HIZO bulk. Although Mo is a widely used interconnect material in AMLCD panels, electrode materials with a low resistivity such as copper (Cu) must be used for fast frame rates (>240 Hz) and large area (>70 in.) displays so as to minimize the signal delay over large distances. In addition, since Cu does not adhere well to oxides, an adhesion layer—for instance titanium (Ti)—is usually grown prior to the deposition of Cu.6,7 In the present work, the characteristics of SiN$_x$-passivated HIZO TFTs that employ two different source/drain electrodes, Mo and Ti/Cu bilayer, are compared.

The devices were fabricated by sputter depositing a 200 nm thick Mo gate, and subsequently growing a dielectric stack of a 400 nm thick SiN$_x$ and a 50 nm thick SiO$_x$ by plasma enhanced chemical vapor deposition (PECVD). A 40 nm thick active HIZO layer was formed by direct current sputtering. A 100 nm thick SiO$_x$ etch stopper layer was then deposited by PECVD. For one type of device (called “Mo device” hereafter), a 200 nm thick Mo was sputtered to form the source-drain electrodes. For the other type of device (called “Ti/Cu device” hereafter), a 20 nm thick Ti layer was sputtered, followed by the sputter growth of a 300 nm thick Cu layer. A 100 nm thick SiN$_x$ passivation was deposited by PECVD on top of the TFT stack. All patterning was done by photolithography and appropriate use of wet or dry etching. The above transistors were then annealed in air for 1 h at 300 °C. Devices with physical channel width/length =25/10 μm were characterized using a Keithley 4200-SCS parameter analyzer, and the threshold voltage ($V_T$), subthreshold swing (S) and saturation field effect mobility ($\mu_{FE}$) were extracted in compliance with the gradual channel approximation. Figure 1 shows a cross-sectional diagram of the inverted-staggered bottom gate TFT and the measurement schemes.

The parameters extracted from the transfer characteristics measurements are listed in Table I. While the mobility is higher for the Mo device, the Ti/Cu device exhibits improved S and $V_T$ values. The transfer curves for both types of devices are shown in Fig. 2. The two devices differ only in the electrode material, which leads us to suspect that the contact between the electrodes and the active layer probably played a

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**FIG. 1.** (Color online) Cross-sectional diagram of the bottom gate, inverted staggered thin film transistor devices with a SiO$_x$ etch stopper, and a SiN$_x$ passivation. The source-drain metals consist of either molybdenum (Mo) or a titanium/copper (Ti/Cu) bilayer.

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TABLE I. Initial transfer characteristics of the devices.

<table>
<thead>
<tr>
<th>Device</th>
<th>$\mu_{FE}$ (cm$^2$/V s)</th>
<th>$V_T$ (V)</th>
<th>$V_{1/2}$ (V)</th>
<th>$S$ (V/decade)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo</td>
<td>8.92</td>
<td>-2.94</td>
<td>-4.38</td>
<td>0.57</td>
</tr>
<tr>
<td>Ti/Cu</td>
<td>5.07</td>
<td>1.16</td>
<td>0.13</td>
<td>0.33</td>
</tr>
</tbody>
</table>

major role in producing such disparate transfer characteristics. We employed the well known transfer length method to extract the contact resistance. The TFT on-resistance ($R_{on}$) may be defined as the sum of the channel resistance ($R_{ch}$) and the source-drain contact resistance ($R_{sd}$) by the following equation:

$$R_{on} = \frac{V_D}{I_D} = R_{ch} + R_{sd} = \frac{L - \Delta L}{\mu_{eff} C_{ox} W (V_G - V_T)} + R_{sd},$$

where $L$ is the physical channel length, and the effective length is defined by $L_{eff} = L - \Delta L$. Here, $\Delta L$ is an apparent channel length reduction that can be seen in a resistance versus $L$ graph measured at various gate voltages, as shown in Fig. 3. The effective mobility, $\mu_{eff}$, is the field effect mobility value that is obtained by replacing $L$ with $L_{eff}$, and $C_{ox}$ is the gate dielectric capacitance per unit area. Devices with different physical lengths ($L$) were selected and the width-normalized total resistance ($R_{on}W$) values were computed from the corresponding transfer curves at different gate voltages. Figure 3 is a set of such plots for the Mo and Ti/Cu devices.

In compliance with Eq. (1), the width-normalized contact resistance ($R_{sd}W$) for the Mo device is 52 $\Omega$ cm, and that for the Ti/Cu device is higher (89 $\Omega$ cm). It is worthwhile considering the different effective channel length reduction ($\Delta L$) in the two types of TFTs. $\Delta L$ for the Mo device is approximately 7.5 $\mu$m, whereas it is only about 3 $\mu$m in the Ti/Cu device. The physical channel length ($L$) is the shortest distance between the source and drain electrodes in contact with the HIZO, and is equal to the etch stopper length in the two types of TFTs. The electrode/HIZO interfaces were also examined by cross-sectional transmission electron microscopy (TEM) as shown in Fig. 4. The electron micrograph discloses no interfacial layer between Mo and HIZO. However, the interface between the Ti adhesion layer and the underlying HIZO shows the presence of an amorphous TiO$_x$ layer, approximately 15 nm thick (Fig. 4). Secondary ion mass spectroscopy and x-ray photoelectron spectroscopy analyses on HIZO/Ti film stacks indicate that the Ti layer mainly consumed oxygen from the underlying HIZO to produce the TiO$_x$ layer (data not shown here). The formation energy of titanium oxide ($-968$ kJ/mol) is lower than that of indium oxide ($-909$ kJ/mol) and zinc oxide ($-581$ kJ/mol), but...
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higher than that of hafnium oxide (−1,088 kJ/mol).\textsuperscript{10} It may thus be anticipated that the titanium layer would preferentially consume oxygen from zinc oxide and indium oxide. In the above analytical experiments, metallic indium is found to diffuse across the TiO\textsubscript{x} film and segregate on the opposite side of the HIZO, leaving a region rich in hafnium and zinc in the semiconductor.

Shown in the insets in Fig. 2 are simplified schematic energy band diagrams that illustrate the difference between the Mo/HIZO and the Ti/HIZO contact. Titanium oxide is a material that is in general known to be an excellent insulator (often used as gate dielectric material), or a semiconductor that exhibits very low field effect mobility (<1 cm\textsuperscript{2}/V s) when incorporated into TFTs.\textsuperscript{11–14} Thus, while direct charge injection from the Mo into HIZO is possible, the carriers have to tunnel through the TiO\textsubscript{x} energy barrier in case of the Ti/Cu device. Consequently, charge injection from the source into the HIZO semiconductor is more limited in the latter, which may account for the higher contact resistance and smaller $\Delta L$. As the gate voltage is swept from negative to positive values, the presence of such an insulating barrier would delay the threshold point until a sufficiently positive gate voltage is reached, and hence the Ti/Cu device operates in enhancement mode despite the SiN\textsubscript{x} passivation that renders the HIZO very conductive. AMLCD panels of the latest generation necessitate switching elements with a steep subthreshold swing and field effect mobility higher than 5 cm\textsuperscript{2}/V s. Also, in order to integrate oxide semiconductors as peripheral circuit elements, the gate voltage that produces a drain current of 1 nA (V\textsubscript{1} nA) needs to remain within 0.0 ± 1.0 V. Accordingly the Ti/Cu device is more favorable than the Mo device.

In summary, the electrical characteristics of SiN\textsubscript{x}-passivated bottom gate HIZO TFTs using Mo and Ti/Cu bilayer electrodes were investigated. The Mo device exhibits higher field effect mobility but poor subthreshold swing, and operates in depletion mode. On the other hand, the TFT employing Ti/Cu bilayer electrodes presents improved subthreshold swing and enhancement mode operation, while preserving sufficiently high field effect mobility. It is suggested that the formation of an insulating TiO\textsubscript{x} layer at the Ti/HIZO interface may be the key parameter that increases the electrode/HIZO contact resistance and results in improved device performance.