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Specific contact resistance of IGZO thin film transistors with metallic and transparent conductive oxides electrodes and XPS study of the contact/semiconductor interfaces

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A B S T R A C T

In this work, the specific contact resistance (ρ_c) between amorphous indium-gallium-zinc-oxide (IGZO) semiconductor and different contact electrodes was obtained from thin film transistors (TFTs). Ti/Au (10/100 nm), aluminum doped zinc oxide (AZO, 100 nm) and indium tin oxide (ITO, 100 nm) were used as source/drain electrodes to fabricate IGZO TFTs. Chemical states of the contacts/semiconductor interfaces were examined by depth profile X-ray photoelectron spectroscopy (XPS) analysis to explain the origin of the differences on specific contact resistance. The lowest ρ_c achieved using Ti/Au was related to the formation of a TiO_x interlayer due to oxygen atoms diffusing out from the semiconductor under layer, increasing the carrier concentration of IGZO at the interface and lowering the ρ_c. On the contrary, no interfacial reactions were observed between IGZO and AZO or ITO source/drain. However, IGZO resistivity increased with ITO contacts likely due to oxygen vacancies filling during ITO deposition. This fact seems to be the origin of the high contact resistance between IGZO and ITO, compared to IGZO-AZO and IGZO-Ti/Au interfaces.

1. Introduction

In recent years, the demand for materials suitable for applications in large area and high resolution displays has increased. Commercially, this technology has been based on hydrogenated amorphous silicon (a-Si:H) TFTs, owing to advantages such as a relatively low temperature ($< 350\,^{\circ}C$) and a straightforward fabrication process. However, one of the major withdrawals of this material is its low mobility ($\sim 1\ cm^2/V\text{-}s$), which restricts its application on high speed or large current demanding devices [1–3]. Moreover, instabilities issues under illumination or bias stressing have been consistently reported for electronic devices based on a-Si; H [4]. Recently, ionic amorphous oxide semiconductors (IAOS) such as IGZO have been proposed as an attractive alternative to overcome these limitations, since Yabuta et al. reported a high performance TFT using this semiconductor as the active layer [5]. Nowadays, most efforts have focused on IGZO TFTs electrical performance improvements and, as a consequence, field effect mobilities of up to $174\ cm^2/V\text{-}s$, low threshold voltages (< 1 V), low subthreshold swing (< 100 mV/decade) and large $I_{on/off}$ ratios (10^8) have been reported [6–8]. Several studies have demonstrated that the contact/semiconductor interface plays an important role on the electrical performance of oxide based TFTs [9–11]. Contact resistance (R_c) is traditionally extracted to evaluate the quality of metal-semiconductor interfaces, but its value depends on the semiconductor sheet resistance and the contact area. In contrast, specific contact resistance is a more meaningful parameter since it is based on a unit area independent from the contact geometry [12,13]. Since the work function of n-type IGZO is ~ 4.5 eV [13], metals with lower work function such as Al, Ti, Cu or Mo are often used as source/drain electrodes, allowing an Ohmic contact formation [15,16]. Nevertheless, it has been demonstrated that contact resistance depends not only on the electrode's work function but also on the chemical states at the interface, which can be modified due to chemical reactions during deposition or postdeposition treatments. For example, some studies have shown evidence of the formation of oxide interlayers such as TiO_x or AlO_x between oxide semiconductors and Ti or Al electrodes [11,17,18]. Other metals, such as Cu, Mo, and Sn, diffuse into the

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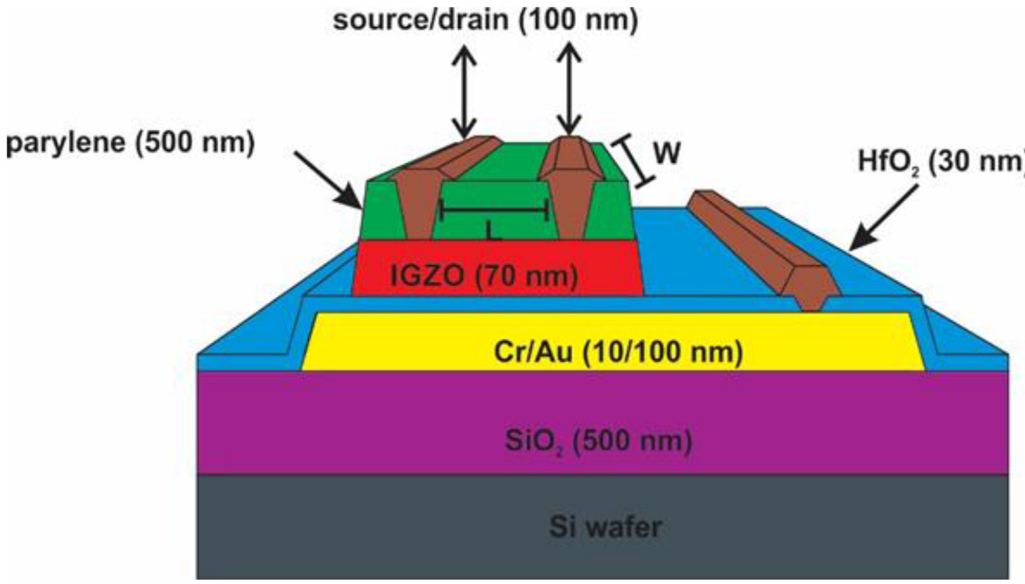

Fig. 1. Schematic of the bottom gate top contact IGZO TFT structure fabricated for this study.

channel layer, acting either as donors or acceptors [19–21]. Although many studies have been conducted to understand the interface between oxide semiconductors and metallic contacts, very few reports have focused on interfaces with transparent conductive oxides (TCOs) as source/drain material [21–23]. This is important because of the increasing demand for transparent electronics which also requires the use of transparent contact electrodes. In this context, several reports have demonstrated the fabrication of IGZO TFTs with excellent electrical performance using IGZO transparent electrodes [23,24]. In this work, we fabricated fully patterned IGZO TFTs using metallic and TCOs contacts, namely Ti/Au, AZO and ITO. The specific contact resistance was extracted from TFTs output characteristics. The latter is a more reliable method since the measurements is performed in the final TFT device rather than isolated testing structures. The electrical performance of these devices was related to the specific contact resistance and explained in terms of the semiconductor/contact interfacial reactions, which were studied by depth profile XPS analysis.

2. Materials and methods

IGZO TFTs were fabricated with a bottom gate-top contact configuration on silicon wafers with 500 nm of thermally grown SiO_2. The gate electrode was formed by a Cr (10 nm)/Au (100 nm) layer deposited by e-beam and patterned by photolithography and wet etching. Next, a 30 nm thick high-k hafnium oxide (HfO_2) gate dielectric was grown by atomic layer deposition at 100 °C, followed by IGZO (70 nm) deposition by pulsed laser ablation at 100 °C and 2.66 Pa of oxygen pressure. After semiconductor deposition, the entire stack was annealed at 200 °C in an oxygen environment for 1 h. Semiconductor thickness, deposition and annealing parameters were previously optimized by simple common gate devices to obtain n-type working devices. The final layer before the contact deposition, consisted on 500 nm of parylene-C used as a hard mask to protect the channel area during the following fabrication steps. To compare the impact of metallic and TCO electrodes on the TFTs performance, different source and drain materials were evaluated: Ti/Au (10/100 nm), AZO (100 nm) and ITO (100 nm). Metallic contacts were deposited by e-beam and TCOs were obtained by pulsed laser ablation in an oxygen environment. Deposition pressure and temperature were 0.13 Pa at 100 °C for AZO and 1.33 Pa at room temperature for ITO electrodes, respectively. The subsequent fabrication was carried out using photolithography as well as dry and wet etching processes. The electrical performance of the IGZO TFTs was measured in dark and room temperature conditions, using a Keithley 4200 semiconductor characterization system. Transfer (I_D vs. V_G) and output (I_D vs. V_D) characteristics were measured in a total of nine devices with different channel widths (40, 80 and 160 µm) and lengths (20, 40 and 80 µm), for each source/drain material. For the transfer curves in saturation, gate voltage (V_G) was swept from −2.5–10 V with a 0.1 V step, setting the drain voltage at 10 V. In the case of the output characteristics, drain voltage (V_D) was varied from 0 to 10 V with a 0.1 V step while stepping V_G = 0, 2, 4, 6 8 and 10 V. The work function of IGZO, Ti/Au, AZO and ITO films was measured with a Kelvin Probe System (SKP 5050, KP Technology), using a 100 nm thick Au (ϕ = 5.15 eV) film as the reference material. A total of 30 readings were acquired and the mean work function value was calculated for all the films. Additionally, HfO_2/IGZO/contacts stacks were fabricated in parallel with TFTs to ensure identical processing. These structures were used to investigate the chemical state of the interface between semiconductor and electrodes by XPS analysis. Depth profile XPS was carried out employing a PHI Versa Probe system, equipped with an Al K_α source and Ar^+ sputtering gun for depth profiling.

3. Results and discussion

3.1. TFTs electrical characteristics

Extracted work function mean values for Ti/Au, ITO, AZO and annealed IGZO films were 4.30, 4.52, 4.56 and 5.01 eV, respectively. Since all the contacts have work function values lower than the n-type IGZO, an Ohmic behavior is expected, regardless of the electrode. From this statement, it is assumed that any difference in electrical performance might be primarily due to contact-semiconductor interface. A schematic cross section of the final devices is shown in Fig. 1. Representative transfer and output curves for IGZO TFTs with a channel width of 80 µm (W) and 20 µm of channel length (L), using Ti/Au, ITO and AZO contacts, are presented in Fig. 2a and b, respectively. Regardless of the TFT dimensions, all the devices exhibited typical n-type TFTs performance with on/off current ratio ($I_{on/off}$) ranging from 10^8 to 10^9 and subthreshold swing (SS) close to 100 mV/dec. Field effect mobility (μ_{FET}) and threshold voltage (V_{th}) were calculated from the $I_D^{1/2}$ vs V_G plot in the saturation regime, using the following equation [25]:

$$I_D = C_i \frac{W}{2L} \mu_{FET} (V_G - V_{th})^2 \tag{1}$$