0.6V Threshold Voltage Thin Film Transistors with Solution Processable Indium Oxide (In$_2$O$_3$) Channel and anodized high- κ Al$_2$O$_3$ Dielectric

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Abstract— **Low voltage operation and low processing temperature of metal oxide transistors remains a challenge. Commonly metal oxide transistors are fabricated at very high processing temperatures (above 500°C) and their operating voltage is quite high (30 – 50 V). Here, thin film transistors (TFT) are reported based upon solution processable indium oxide (In$_2$O$_3$) and room temperature processed anodized high-κ aluminum oxide (Al$_2$O$_3$) for gate dielectrics. The In$_2$O$_3$ TFTs operates well below V$_{ds}$ of 3.0 V, with on/off ratio 10^5, subthreshold swing (SS) 160 mV/dec, and low threshold voltage V$_{th}$ 0.6 V. The electron mobility (μ) is as high as 3.53 cm^2/V.s in the saturation regime and transconductance g$_m$ 53 μS. Furthermore, the detailed capacitance voltage (C-V) analysis also investigated, the measurements shows low leakage gate current. Additionally, the interface trap density (D$_{it}$) in the oxide/semiconductor interface was quite low i.e. 0.986 × 10^{11} – 2.98 × 10^{11} eV^{-1}.cm^{-2}, signifying decent compatibility of In$_2$O$_3$ with anodic Al$_2$O$_3$.**

Index Terms— **Metal oxide semiconductors, Solution processable indium oxide (In$_2$O$_3$), Low voltage TFT, anodization.**

I. INTRODUCTION

Metal oxide semiconductors have been extensively studied in the last few years for a wide range of devices and device applications such as thin film transistors (TFT) for transparent and flexible electronics, active matrix and flat panel displays, bio/medical sensors, and radio frequency (RF) circuits [1-3]. Metal oxide semiconductors gained special attention due to their diverse spectrum of properties that distinguishes them from those of conventional silicon, such as wide band gap, wide optical transparency, high mobility and low temperature solution processable deposition [4]. They have paved the way for the next generation thin film and printed electronics [5]. Amongst all the metal-oxide semiconductors, indium oxide (In$_2$O$_3$) is the most favorable n-type semiconductors for thin film transistors with a band gap 3.6 – 3.75 eV and high carrier mobility [6]. However, most of the reported research on indium oxide thin film transistors has been based upon vacuum deposition techniques and high temperature annealing, with very high operating voltage 30 – 50 V [7, 8]. On the other hand,

thin film transistors based on solution processes has many desirable manufacturing advantages over the conventional vacuum deposition processes, such as low cost, high yield and ease of processing [9, 10]. Although remarkable progress has been made, metal oxide thin film transistors still pose significant challenges, such as operating voltage, switching speed and on/off ratio.

Here we fabricated TFTs based upon In$_2$O$_3$ channels by combining the solution-processing route for the semiconductor and an anodization technique for the high-κ aluminum oxide Al$_2$O$_3$ gate dielectric, which enables a low operating voltage i.e. < 3V device operation. The anodization process was carried out as reported previously [11]. Anodization empowers the room temperature deposition of dielectric, bypassing high temperature, high vacuum processes, with added advantages such as nanoscale deposition, high quality and denser oxide layers to prevent gate leakage current [12]. Furthermore, the anodization process is a low cost, room temperature process, compatible with flexible and printed electronics devices. The detailed analysis of its electrical performance and thorough analysis of MOS capacitors for the interface strap states density was also investigated.

II. EXPERIMENTAL

The bottom gate, top contact (BGTC) topology was used here for the device fabrication as shown in Fig. 1. TFTs were fabricated on glass substrates. Prior to device fabrication, the glass substrates were ultrasonically cleaned with acetone, IPA and deionized water for 30 minutes sequentially. Initially, to form a gate contact, 100 nm of aluminum (Al) metal was
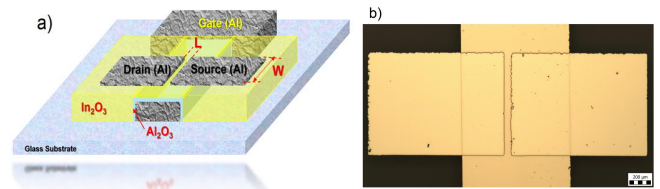

Fig. 1. a) Schematic structure of the ln$_2$O$_3$ TFT with Al$_2$O$_3$ gate dielectric. b) Optical image of the fabricated ln$_2$O$_3$ TFT with 70 μm gate length.

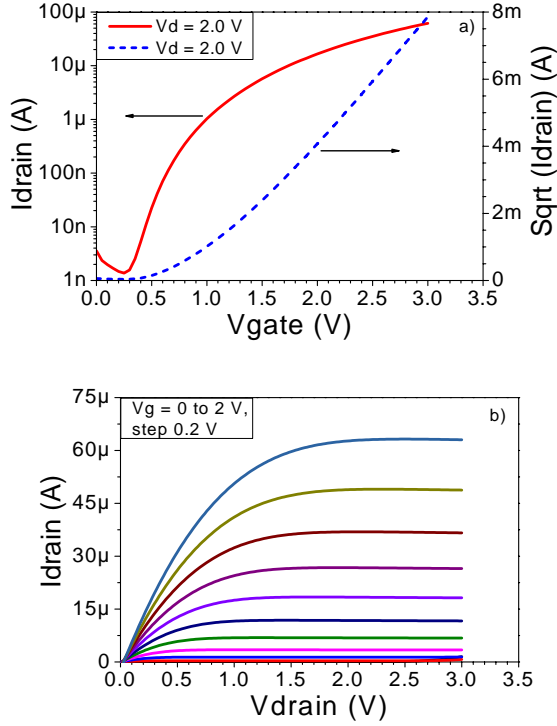deposited on a glass substrate using a shadow mask for patterning.

Fig. 2. a) Transfer characteristics of In_2O_3 TFTs with 70 µm gate lengths and b) Output characteristics for In_2O_3 TFTs with 70 µm gate lengths.

The anodization process was performed next to convert a top surface (~10 nm) of the aluminum metal into a high-κ dielectric, Al_2O_3. After the anodization, the substrates were thoroughly washed with deionized water. Subsequently, the solution processed In_2O_3 semiconductor channel was deposited atop by first spin coating, followed by two-step annealing at 90 °C and at 300 °C for 15 min and 30 min in air, respectively. Furthermore, the In_2O_3 solution was prepared by dissolving Indium (III) nitrate hydrate $In(NO_3)_3 \cdot xH_2O$ in anhydrous 2-methoxyethanol 99.8% in 0.2 M concentration as reported by Ari Alastalo *et al*. [13]. The solution was stirred for 12 hours at 75 °C prior to spin coating. All the precursors were purchased from Sigma-Aldrich and used as-is without any further distillation. Finally, 100 nm of Al metal was deposited to form the drain and source electrodes. The channel width (W) and length (L) was 700 µm and 70 µm, respectively. The Al metal evaporation was performed using an e-beam evaporator under a high vacuum 10^{-6} Torr. Under the same conditions as the TFTs, MOS test structures consisting of $Al/Al_2O_3/In_2O_3/Al$ were also fabricated on the same substrates.

The electrical characterization (I-V and C-V) of the In_2O_3 TFTs were performed using a Cascade probe station connected to the semiconductor device parameter analyzer (Keysight B1500A) with triaxially shielded probes.

III. RESULTS AND DISCUSSION

The transfer (I_d vs V_g) and output (I_d vs V_d) characteristics of the TFTs devices consisting of In_2O_3 as the semiconductor channel with anodized Al_2O_3 as the gate dielectrics are shown

in Fig. 2. The devices exhibits n-channel behavior, with a very low operating voltage, 3 volts, and the threshold voltage, V_{th} is determined to be 0.6 V, which is much smaller than that of TFTs fabricated with conventional SiO_2 gate dielectric [14]. The operating voltage of the In_2O_3 TFTs with Al_2O_3 make them an ideal choice for integrated circuits (IC) applied to wearables and IoT applications where autonomous power sources would be depleted by TFTs operating at low voltages.
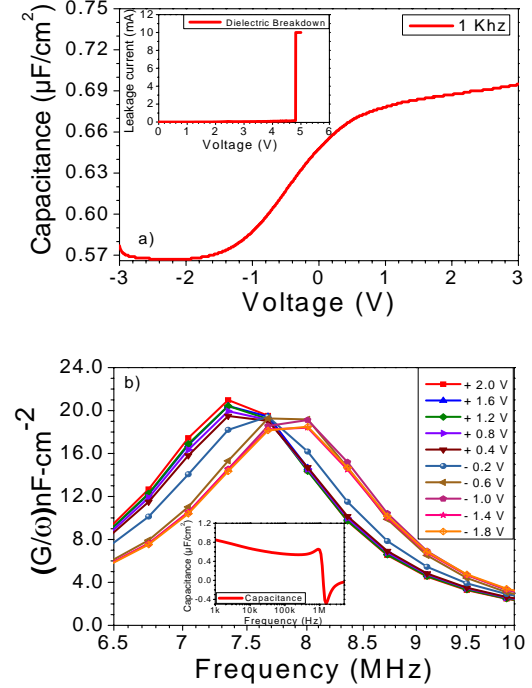

Fig. 3. a) Capacitance voltage characteristics of In_2O_3/Al_2O_3 MOS device measured at 1 KHz frequency. Inset: Breakdown voltage and b) G/ω vs ω characteristics representing conductance at selected bias voltage. Inset: capacitance vs. frequency

The devices exhibits on/off ratio ~10^5 and the electron mobility (µ) was measured as high as 3.53 $cm^2V^{-1}s^{-1}$ in saturation regime calculated using the equation

$$\mu_{(sat)} = \frac{\left(\frac{\partial (\sqrt{I_D})}{\partial V_G} \right)^2}{\frac{1}{2} C_G \frac{W}{L}}$$

Where, I_D is the drain current, V_G is the gate voltage, C_G is the gate oxide capacitance, and W/L is the ratio of width to length of the TFT channel. The gate oxide thickness were estimated from the capacitance voltage curve shown in Fig. 3 (a) and was extracted to be ~ 8 nm. The Al_2O_3 formed with anodization, exhibits a very low leakage current below the measured breakdown field of 6.07 MV/cm [Fig 3 (a) inset]. The TFT transconductance (g_m) gain is as high as 53 µS. Furthermore, the subthreshold swing S was only 0.16 V/dec., which is comparatively quite low compared to the previously reported [15]. This implies there is a lower defect density of states within the gate oxide. As shown in the Fig. 3 (b) inset, the capacitance per area of the MOS structure show high values (0.6 - 0.8 µF/cm²) over a flat frequency response from 1 KHz to 1.3 MHz shows the good dielectric properties.

To investigate this further, we have calculated the interface

trap density (D_{it}) in the oxide by using the conductance method by sweeping from 1 KHz to 5 MHz [16],

$$D_{it} = \frac{2.5}{q}\left(\frac{G_p}{\omega}\right)_{max}$$

Where, G_p is the peak conductance per unit area, $\omega = 2\pi r f$ (f - frequency), and q is the electronic charge. To calculate the interface trap density (D_{it}), (G_p/ω) was plotted as a function of frequency. As shown in the Fig. 3 (b), as the frequency increases, G_p/ω also increases and reaches its maximum and as expected with an interface trap model, G_p/ω starts to decrease with further increase in frequency [17].
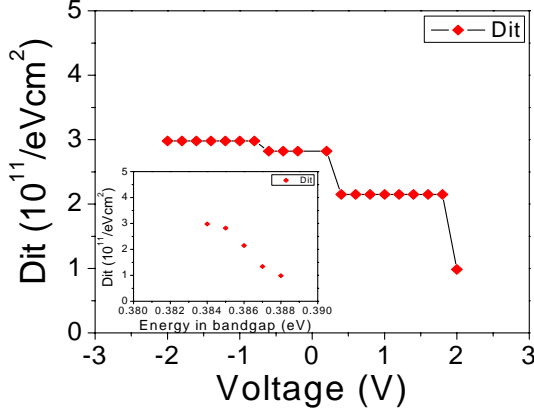

Fig. 4. Trap states density as function of biasing voltage, Inset: Trap states density as a function of energy.

The interface trap density extracted using the measured maximum conductance [18] was about $0.986 \times 10^{11} - 2.98 \times 10^{11}$ eV^{-1}.cm^{-2}. The subsequent relationships among trap states densities with biasing voltage dependence and their energy levels are represented in the Fig. 4. Summarized results of In$_2$O$_3$ TFT performance parameters are shown in Table 1.

IV. CONCLUSION

TABLE I
SUMMARIZED IN$_2$O$_3$ TFT PERFORMANCE PARAMETERS

V_{th} (V)	μ_{sat} (cm^{2}V^{-1}s^{-1})	Gm (μS)	SS (V/dec)	I_{on}/I_{off}	D_{it} (eV^{-1}.cm^{-2})
0.6	3.5	53	0.16	~10^5	$0.986 – 10^{11}$

Thin film transistors (TFTs) based on low-temperature, solution-processable indium oxide (In$_2$O$_3$) with a very thin (< 10nm) anodic aluminum oxide Al$_2$O$_3$ as gate dielectric were demonstrated here with very low voltage device operation. The TFTs shown very good low voltage performance below 3.0 V and the electron mobility (μ) is as high as 3.53 cm^2/V.s. Furthermore, we also investigated that the dielectric properties of the anodic aluminum oxide Al$_2$O$_3$ and its estimated interface trap density, D_{it} about $0.986 \times 10^{11} - 2.98 \times 10^{11}$ eV^{-1}.cm^{-2}, suggests a very good compatibility of indium oxide (In$_2$O$_3$) with anodic aluminum oxide Al$_2$O$_3$. This study shows the low temperature fabrication compatibility for solution-processable metal oxide semiconductors for flexible and printed electronics devices.

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