2-volt Solution-Processed, Indium Oxide (In_2O_3) Thin Film Transistors on flexible Kapton

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Abstract— **Semiconductor devices based upon silicon have powered the modern electronics revolution through advanced manufacturing processes. However, the requirement of high temperatures to create crystalline silicon devices has restricted its use in a number of new applications, such as printed and flexible electronics. Thus, developments with high mobility solution-processable metal oxides, surpassing α-Si in many instances, is opening a new era for flexible and wearable electronics. However, high operating voltages and relatively high deposition temperatures required for metal oxides remain impediments for the flexible devices. Here, the fabrication of low operating voltage, flexible thin film transistors (TFT) using a solution processed indium oxide (In_2O_3) channel material with room temperature deposited anodized high-κ aluminum oxide (Al_2O_3) for gate dielectrics are reported. The flexible TFTs operates at low voltage V_{ds} of 2 V, with threshold voltage V_{th} 0.42 V, on/off ratio 10^3 and subthreshold swing (SS) 420 mV/dec. The electron mobility (μ), extracted from the saturation regime, is 2.85 cm^2/V.s and transconductance, gm, is 38 μS.**

I. INTRODUCTION

Metal oxide semiconductors have gained significant attention during the past couple decades owing to their superior optoelectronics properties, such as wide band gap, charge transport mechanism, and thin film deposition techniques allowing for a new paradigm in electronics devices [1-2]. Amorphous metal oxide semiconductors have been widely studied for numerous opto-electronic, sensing and medical applications. Among all metal oxide semiconductors, indium oxide (In_2O_3) is a very promising candidate for the thin film transistor due to its attractive electrical performance [3-4]. However, despite significant progress, the goal of low-cost – low temperature deposition of metal oxides still faces major challenges. As most of the required device fabrication process steps use high temperature deposition techniques, especially for the gate oxide deposition, such as vacuum-based thin film deposition, metal oxide TFTs on flexible substrates remains elusive [5]. Thus, efforts have been taken to develop a low temperature, low-cost solution processable deposition process for metal oxide TFTs [6]. And even though, some progress has been made towards flexible TFTs, major challenges remain in terms of high operating voltage.

Herein, the fabrication of low operating voltage flexible thin film transistors has been reported. The TFTs were fabricated on flexible Kapton substrates using a solution processed indium oxide (In_2O_3) semiconductor as the TFT channel material with room temperature anodized high-κ aluminum oxide (Al_2O_3) gate dielectric [7-9].

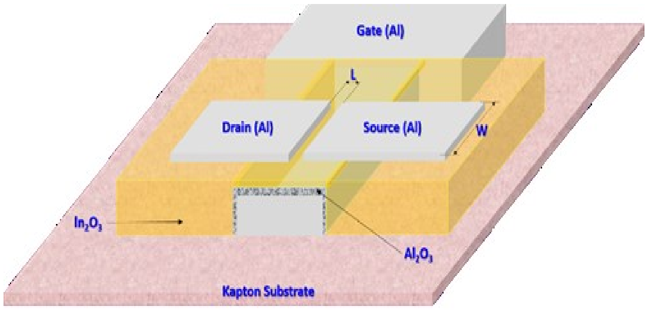

Fig. 1. Schematic structure of the In_2O_3 TFT with Al_2O_3 gate dielectric.

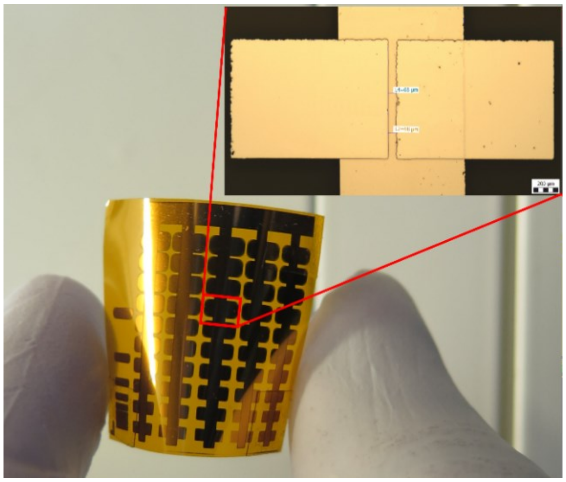

Fig. 2. Photograph of the In_2O_3 TFT fabricated on the flexible Kapton substrate, Inset: Optical image of In_2O_3 TFT with 70 μm gate length. Scale bar 200 μm.

II. EXPERIMENTAL

The schematic representation of the flexible TFTs is shown in Fig. 1. The TFTs, were fabricated on the flexible Kapton substrate with the use of bottom gate top contact (BGTC) topology, following a previous approach used by the authors atop glass that resulted in ultra-low threshold voltages [9].

Photograph of the In_2O_3 TFTs fabricated on the flexible Kapton substrate and optical image with 70 µm gate length is shown in Fig. 2 and Inset, respectively. Scale bar 200 µm.The Kapton substrates were thoroughly cleaned before the device fabrication, using acetone, isopropanol (IPA) and deionized water (DI) for 30 minutes successively. The top gate contact was formed by depositing the 100 nm aluminium (Al) using a patterned shadow mask. Subsequently, the anodization process has been performed to convert top 10 nm layer of the gate contact into the aluminium oxide, i.e. the high-κ gate dielectric. The substrates were cleaned thereafter several times with deionized water to purge any residual ions. Next followed was the indium oxide, In_2O_3, deposition by spin coating a precursor film and annealing in air at 90 °C for 15 min. and 300 °C for 30 min. for conversion. Prior to spin coating, the indium oxide (In_2O_3) ink 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 [9], and stirring for 12 hours at 75 °C. All precursors used as-is without any further distillation and were purchased from Sigma-Aldrich. After the spin coating, the drain and source contacts of 100 nm thick aluminium (Al) was deposited using a shadow mask. The aluminium (Al) metal deposition was carried out under a high vacuum 10^{-6} Torr, using an e-beam evaporator. Furthermore, to perform the capacitance voltage (CV) analysis, on the same substrates and the under same conditions, MOS (Metal-Oxide-Semiconductor) test device comprised of $Al/Al_2O_3/In_2O_3/Al$ were also fabricated.

The electrical performance (I-V and C-V) of the flexible In_2O_3 TFTs was carried out with the aid of a Cascade probe station connected to a Keysight B1500A semiconductor device parameter analyzer with triaxially shielded probes.

III. RESULTS AND DISCUSSION

The output (I_d vs. V_d) and transfer (I_d vs. V_g) characteristics of the fabricated flexible TFTs using the In_2O_3 semiconductor channel material and anodized Al_2O_3 gate dielectrics are shown in Fig. 3 and 4, respectively. The flexible TFTs operates at very low-voltage, i.e. 2 volts with a very low threshold voltage, V_{th}, 0.42 V, significantly smaller than previously reported metal oxide TFTs on flexible substrates [10].

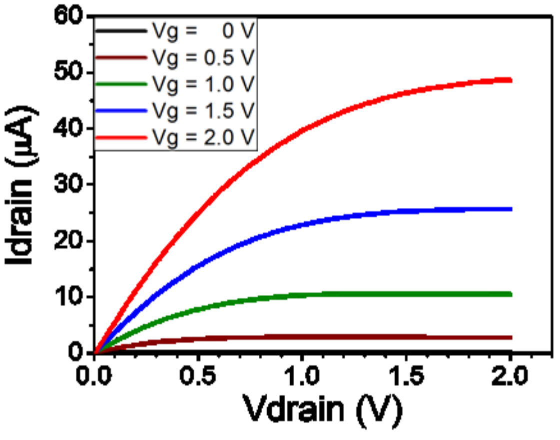

Fig. 3. Output characteristics for In_2O_3 TFTs with 70µm gate length.

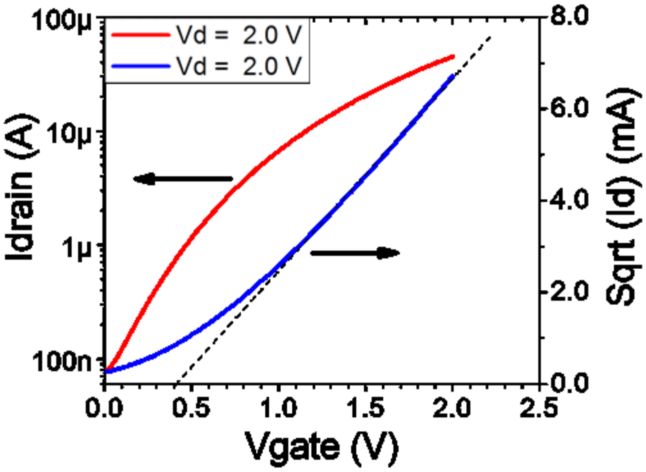

Fig. 4. Transfer characteristics of In_2O_3 TFTs with 70µm gate.

The electron mobility (µ) in the saturation regime was found to be 2.85 $cm^2V^{-1}s^{-1}$, 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.

Furthermore, the on/off ratio was up to $\sim 10^3$. The TFT transconductance (g_m) gain was as high as 38 µS and the subthreshold swing, SS, extracted was 0.42 V/dec.

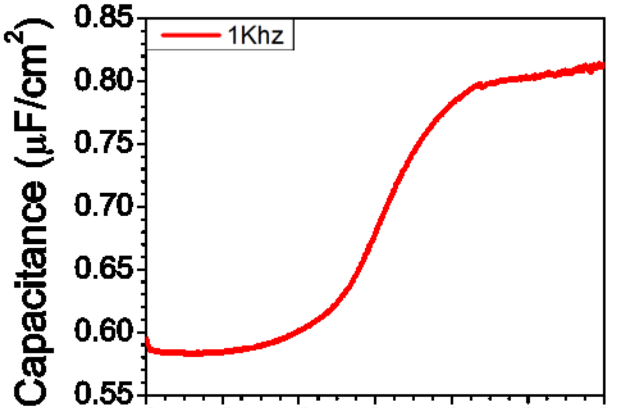

Fig. 5. Capacitance voltage characteristics of In_2O_3/Al_2O_3 MOS device measured at 1 KHz frequency.

The gate oxide thickness was found to be ~8nm and was calculated from the MOS capacitance voltage analysis as shown in Fig. 5. Our previous report [9] confirmed with transmission electron microscopy the close agreement the physical thickness with extracted electrical thickness. The dielectric constant, κ was found to be 9.3, as calculated using parallel plate capacitance equation, $C = \kappa\varepsilon_0 A/d$ [11]. The gate dielectric formed with the anodization exhibits quite low leakage current, i.e. below 1.5 V as shown in Fig. 6, and demonstrates the good dielectric properties of anodized aluminium oxide.

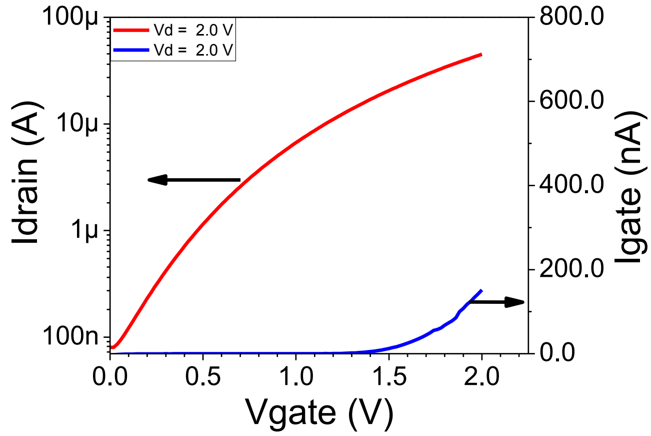

Fig. 6. Transfer characteristics of In_2O_3 TFTs showing gate leakage current with 70μm gate.

Table 1. Shows the combined results of electrical performance of the flexible indium oxide (In_2O_3) thin film transistors.

TABLE I

SUMMARIZED In_2O_3 TFT PERFORMANCE PARAMETERS

V_{th} (V)	μ_{sat} ($cm^2V^{-1}s^{-1}$)	g_m (μS)	SS (V/dec)	I_{on}/I_{off}
0.42	2.85	38	0.42	$\sim 10^3$

IV. CONCLUSIONS

Thin film transistors (TFTs) using a solution-processable indium oxide (In_2O_3) were fabricated on flexible Kapton substrates. The very thin ~8nm high- κ aluminum oxide (Al_2O_3) gate dielectric was deposited with the help of a room temperature anodization process, enabling low voltage operating devices. The flexible TFTs demonstrates very good low voltage performance at 2.0 V and the electron mobility (μ) is as high as 2.85 cm^2/V.s. In this study, we have successfully demonstrated low voltage TFTs by uniting low temperature solution processable In_2O_3 with room temperature anodized high-κ aluminum oxide Al_2O_3 gate dielectrics.

ACKNOWLEDGMENT

The authors would like to extend a special thanks to Business Finland (40146/14) and the Academy of Finland (311458) for the financial assistance.

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