

# Reactive Deposition of Channel and Insulating Layers for TFT Applications at Ambient Temperatures Using a Remote High Density Plasma

*J.D. Dutson, Plasma Quest Ltd., Hook, United Kingdom; A.J. Flewitt and P. Beecher, Electrical Engineering Division, University of Cambridge, Cambridge, United Kingdom; and S.J. Wakeham and M.J. Thwaites, Plasma Quest Ltd., Hook, United Kingdom*

## ABSTRACT

A novel RF-plasma sputter deposition technique is described in detail for the deposition of critical layers for thin-film transistor applications. Dielectric materials of hafnia and aluminium nitride are described and breakdown of hafnia is measured at an electric field strength of greater than 10MV/cm. Channel layers of zinc oxide and indium zinc oxide have been deposited in thin film transistor structures and the field effect mobility for indium zinc oxide has been measured as  $>10\text{cm}^2\text{V}^{-1}\text{s}^{-1}$  with a switching ratio of  $>10^6$ . The deposition technique described uses reactive depositions of these materials from metallic targets providing a high level of control of the material properties, and significantly enables the deposition of all the materials to be performed in ambient conditions.

## INTRODUCTION

Thin film transistors (TFTs) are required for many technological applications, each of which has its own material requirements. One of the more interesting and technically challenging applications is in active-matrix liquid crystal displays (AMLCDs) where the transistor is used to turn on and off the individual pixel. The requirements for a modern display require the field effect mobility ( $\mu_{\text{FE}}$ )  $>1\text{cm}^2\text{V}^{-1}\text{s}^{-1}$  and ideally greater than  $5\text{cm}^2\text{V}^{-1}\text{s}^{-1}$  with an on/off ratio greater than  $10^6$  whilst commercial considerations make it desirable to be deposited in a low cost and low process temperature environment [1]. The current materials for TFT channel layers are typically hydrogenated amorphous silicon ( $\alpha\text{-Si:H}$ ) films that demonstrate a comparatively poor mobility, typically  $\sim 0.6\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ , and more critically poor levels of stability [2]. Although the properties of  $\alpha\text{-Si:H}$  may be sufficient for AMLCDs the next generation of displays are likely to be based on active-matrix organic light emitting diodes (AMOLED) displays. In this instance, the metastability of  $\alpha\text{-Si:H}$  will preclude traditional TFT solutions for the next generation of devices. Furthermore, it is highly desirable to develop solutions that are based on transparent electronics whilst maintaining the high performance required for these devices. The development of the transparent electronics market is dependent on the ability to deposit transparent transistors relatively cheaply with high quality.

One of the most promising set of materials that can fulfill the specifications for AMLCD and AMOLED technologies are based on zinc oxide (ZnO) films. There has been a substantial amount of research in ZnO films in recent years due to the direct wide band gap ( $E_g=3.3\text{eV}$  at 300K) and comparatively high mobility. Additionally, wide band gap materials are less likely to deteriorate on exposure to visible light compared to silicon-based electronics and consequently there would be no need to shield the active channel layer. ZnO is particularly preferential, as these films also possess high voltage, temperature and radiation tolerance [3]. For TFT applications, it is particularly desirable to grow the ZnO with an amorphous structure to eliminate defects associated with grain boundaries and improve device-to-device uniformity.

ZnO films have been grown for many years using a wide range of techniques including RF magnetron sputtering[4], molecular beam epitaxy [5], pulsed laser deposition (PLD) [6,7], chemical vapour deposition [8] and atomic layer deposition (ALD) [9]. Particularly good quality material has been produced by rf magnetron sputtering, PLD and ALD, but all with comparatively low deposition rates, up to 5 nm/min and in most cases require heating of the substrate to obtain high quality materials. To minimise the cost of the eventual electronic devices, deposition techniques need to be developed where high quality material can be deposited at low temperatures and with a high throughput, potentially suitable for roll-to-roll processing. This work describes a novel deposition technique, High Target Utilisation Sputtering (HiTUS), that is ideally suited for the deposition of amorphous ZnO based films suitable for applications in AMOLED technologies and for transparent electronics more generally.

## HiTUS DEPOSITION SYSTEM

The HiTUS deposition system, shown in Figure 1, is a novel approach to deposition where a high-density,  $\sim 10^{13}/\text{cc}$ , plasma containing only low energy,  $<10\text{eV}$ , ions is formed in a remote Plasma Launch System (PLS). The plasma is confined and directed by the DC electromagnetic field of two electromagnets on to a 4" disc sputter target. The high ion density achieved in the plasma provides a high ion-current density over the whole of the 4" target (compared to a localised ring in magnetron deposition systems). Although there is a high ion current density, the low energy of the ions results in no sputtering occurring, as there is insufficient energy to over-

come the sputtering threshold energy. To achieve sputtering, a suitably large negative electrical bias needs to be applied to the target, which in turn provides the accelerating electric field for the ions to exceed the threshold. The unique nature of the HiTUS deposition system provides independent control of the ion density (controlled by the remote generation) from the ion energy (provided by the target bias). This provides a very wide process space available for depositions compared to similar techniques. For example, process pressure may be varied from  $1 \times 10^{-4}$  mbar to  $5 \times 10^{-2}$  mbar with no modifications required to the set-up and equipment. The presence of the high ion density over the whole of the target enables deposition from the full target, which increases the deposition rate and enables more controlled reactive depositions.

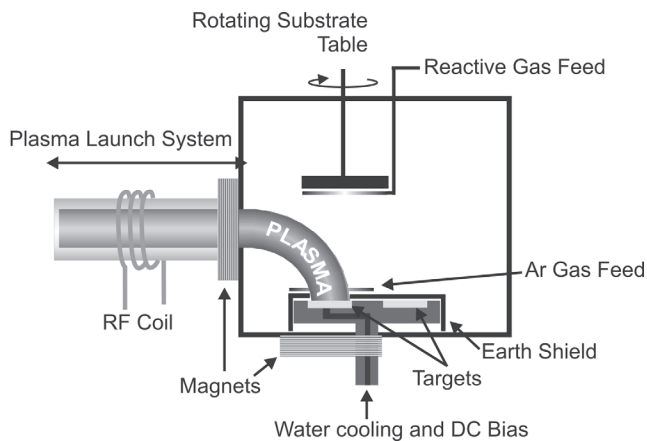


Figure 1: Schematic of HiTUS configuration.

The enabling PLS where the plasma is remotely generated follows a proprietary design described in detail in reference [10]. Simplistically, a helical RF antenna surrounds a 4" diameter quartz tube, which is powered with a 13.56MHz 5kW RF power supply and appropriate matching unit. A DC electromagnet operating at an axial field strength of up to 300 Gauss provides the required interaction with the RF antenna generated plasma to achieve the very high plasma densities. The PLS is fitted as a sidearm unit onto a vacuum deposition chamber. The size of chamber can vary but for this work, it was 400x400x500 mm constructed from 316L stainless steel and pumped with a 1200 l/min turbomolecular pump with an appropriate backing/roughing rotary pump. For use in the sputter configuration shown, the PLS requires an additional DC electro-magnet located below the sputter target assembly. Targets are normal commercially available sputter targets typically 4" diameter x 6 mm deep. The targets are loaded into a water cooled, magnet free rotatable target holder assembly where all the targets are simultaneously biased from a single 12kW DC power supply. The biased areas of the assembly that are not to be sputtered are covered by an earth shield that is kept within the Crookes dark space, thereby preventing local plasma generation. The substrate

table is positioned above the target with a substrate-target separation of 15 cm and, for this work, consisted of an unheated 4" rotating substrate table with a rotation frequency of 1Hz. The target-substrate separation is determined by the need to provide sufficient space to accommodate the plasma but the comparatively large separation also reduces unwanted heating of the substrate from the plasma and target assembly. This enables the critical substrate temperatures to be kept to a minimum during the deposition process despite the absence of substrate cooling, with only moderate heating up to 70°C due to other minor heating sources. Full details of the HiTUS configuration and sputter target operation can be found in [11].

To perform a deposition the chamber is pumped to a base pressure (BP), typically  $< 2 \times 10^{-5}$  mbar, and then research grade argon gas is continuously fed into the chamber to a defined process pressure (PP). Power is then supplied to the electromagnets and then to the PLS RF antenna ( $RF_{\text{launch}}$ ), resulting in the generation of a high-density plasma. The magnet powers are optimised in the original set-up of the equipment and are then kept constant for all materials. The  $RF_{\text{launch}}$  directly controls the ion density, which can significantly affect the material properties of the final film and is used as a major process variable. To achieve sputtering, a target bias is applied,  $DC_{\text{bias}}$ . Prior to deposition, the targets are given sufficient time to sputter to ensure that each deposition is performed from the same target condition, a period defined as target cleaning. If a reactive deposition is required, the reactive gas is then injected at a controlled flow rate in close proximity to the substrate and a period of stabilisation is allowed prior to deposition. Finally, after the target clean and stabilisation steps, the shutter is opened for the deposition.

The HiTUS configuration is normally run in a reactive mechanism to deposit oxide films. This is when a metallic target is sputtered and a reactive gas, typically oxygen, is injected into the chamber. The metal atoms sputtered from the target react with the oxygen at or near the surface of the substrate to form the required oxide film. Traditional deposition techniques have difficulty with this deposition method due a phenomenon known as target poisoning. This is when the reactive gas interacts with the target directly and forms an insulating oxide layer over parts of the target. This can be countered by using active feedback to the target although this complicates the deposition process and is difficult to optimise [12]. Poisoning of the target is often precipitated by the presence of the racetrack in magnetron sputter deposition configurations where sputtering only occurs close to the magnetic ring. In the HiTUS configuration, it is possible to sputter from the whole target and at high deposition rates, which substantially reduces or even prevents the poisoning of the target. The injection of the gas is critical and two separate gas distribution rings for the argon and oxygen are used. The oxygen distribution ring is located close to the substrate with

the direction of oxygen flow directed towards the substrate and the argon ring is located in close proximity to the target. With this configuration, it is possible to sputter oxide films reproducibly through a reactive process and importantly, with no active feedback. All the oxide films described in this paper are deposited reactively.

## DEVICE STRUCTURE AND GROWTH.

The structure of the bottom gate TFT devices structure is shown in Figure 2. The structure consists of a substrate coated with a bottom electrode, referred to as the gate electrode, a dielectric layer to support an electric field referred to as the gate dielectric, a channel layer that consists of the critical semi-conducting material and finally source and drain contacts. High conductivity metal oxides are found to make very good Ohmic contacts with metal oxide semiconductors due to the excellent band line-up of these systems [13]. The most critical layers to achieve good device performance are the gate dielectric and the channel layer. The gate dielectric needs to have high resistivity, breakdown properties and dielectric constants whilst the channel layer must exhibit good mobility, high resistivity and stability.

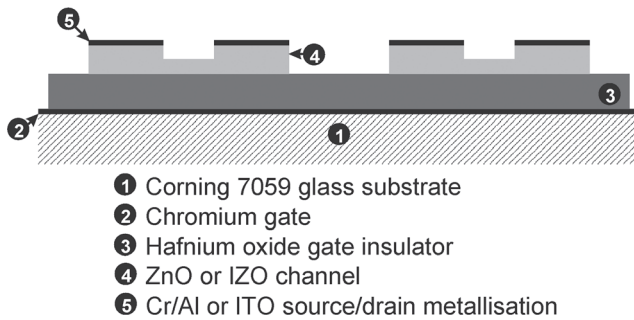


Figure 2: Schematic diagram of the bottom gate inverted staggered TFT structure.

### Gate Dielectrics

Two transparent dielectrics have been evaluated for potential use as gate dielectrics, Hafnia ( $\text{HfO}_2$ ) and Aluminium Nitride (AlN). Hafnia was grown on highly doped silicon wafer substrates with the following conditions:  $\text{RF}_{\text{launch}} = 1.25\text{kW}$ ,  $\text{DC}_{\text{bias}} = 0.8\text{kV}$ ,  $\text{PP} = 7 \times 10^{-3}\text{ mbar}$ ,  $\text{O}_2$  flow = 15 to 30 sccm with a 3 min target clean and 2 min stabilisation period. Although the hafnia was grown with an optimised oxygen flow rate of 20.5 sccm, the window for achieving high deposition rates ( $>30\text{ nm/min}$ ) whilst simultaneously achieving high transparency films ( $>95\%$  peak transmission for 200 nm thick film) was  $>7\text{ sccm}$  of  $\text{O}_2$  flow. The refractive index was measured using ellipsometry and was found to plateau at 2.06 between flow rates of 17.5 sccm to 25 sccm. Deposition rates went through a maximum of 43 nm/min at 20 sccm and then steadily declined to 30 nm/min at 25 sccm. Electronic properties of the hafnia have been characterised by evaporating aluminium dots

onto the films and probing with a Cascade Atto-guard Probe State and measuring with an Agilent B1500A Semiconductor Parameter Analyser or HP4140B picoammeter/voltage source. It was found that material possessed a breakdown strength  $>10\text{ MVcm}^{-1}$  and the dielectric constant  $\sim 22.8$  with resistivity of the film  $2.5 \times 10^{13}\ \Omega\text{cm}$ . Aluminium Nitride was grown using the following conditions:  $\text{RF}_{\text{launch}} = 1.2\text{kW}$ ,  $\text{DC}_{\text{bias}} = 800\text{V}$ ,  $\text{PP} = 3 \times 10^{-3}\text{ mbar}$ ,  $\text{N}_2$  flow = 30-45 sccm with a 3 min target clean and 2 min stabilisation period. For these films, the optimum breakdown of  $3\text{ MVcm}^{-1}$  was measured at 40 sccm  $\text{N}_2$  flow. The breakdown properties of both films are shown in Figure 3.

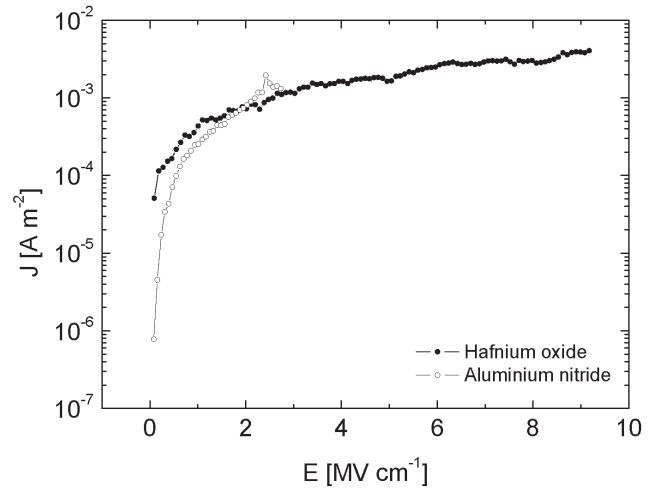


Figure 3: Breakdown characteristics for hafnium oxide and aluminium nitride.

### Channel Layer

Two different films were investigated for the channel layer of these films, zinc oxide (ZnO) and indium zinc oxide (IZO). ZnO films were produced from a 99.999% pure metallic target and deposited with the following conditions:  $\text{BP} = 9 \times 10^{-6}\text{ mbar}$ ,  $\text{PP} = 5 \times 10^{-3}\text{ mbar}$ ,  $\text{RF}_{\text{launch}} = 1.5\text{kW}$  and  $\text{DC}_{\text{bias}} = 700\text{V}$ ,  $\text{O}_2$  flow = 20 to 30 sccm. The target was cleaned for only 20 seconds due to the ability of zinc to sublime and a 2 minute stabilisation period was used. The properties of the ZnO varied significantly with the oxygen flow rate with a resistive layer suitable for the channel with conductivity =  $3 \times 10^{-9}\ \Omega^{-1}\text{m}^{-1}$  with  $>24\text{ sccm}$   $\text{O}_2$  flow. Alternatively, the ZnO could be produced with an oxygen flow rate  $\sim 21\text{ sccm}$  when the conductivity increases by 13 orders of magnitude to as high as  $3 \times 10^4\ \Omega^{-1}\text{m}^{-1}$  whilst still maintaining a high transmission ( $>89\%$  for 110 nm thick film). This different change in properties is important as the same deposition process can be used for both the channel layer and the charge-injection layer for the source/drain electrodes. This is particularly important for keeping the overall manufacturing cost of the complete devices to a minimum. Deposition rates for these films varied depending on oxygen flow rate, but insulating layers were deposited with 25 sccm

$O_2$  at 50 nm/min. X-ray diffraction measurements indicate that the ZnO films have a polycrystalline structure similar to those observed in RF magnetron depositions [14].

IZO films were grown from an In 50%wt.:Zn 50%wt. metal alloy target with the following conditions:  $BP=9 \times 10^{-6}$  mbar,  $PP=5 \times 10^{-3}$  mbar,  $RF_{\text{launch}}=1.25$  kW and  $DC_{\text{bias}}=0.8$  kW,  $O_2$  flow=14 to 25 sccm with a 5 minute target clean to increase reproducibility and a 3 minute stabilisation period. High-resolution TEM images of these films indicate that the structure is amorphous and there is no long-range order [14]. This is potentially advantageous as the presence of grain boundaries can cause defects and increase scattering events thereby reducing mobility. The IZO films were grown onto highly doped n-type silicon wafers with a thick  $2 \mu\text{m}$  coating of thermally grown silicon dioxide to enable accurate measurements of the transfer properties, which are shown in Figure 4. The device structure had a channel length of  $50 \mu\text{m}$  and a channel width of  $11.5 \text{ mm}$  ( $W/L = 230$ ) and followed an inverted staggered structure. Photolithography was performed with an AZ5214 photoresist and patterned with an EVG620 mask aligner. The curing temperature of the photo-resist,  $120^\circ\text{C}$ , defines the maximum temperature the devices were exposed to during the manufacturing process. The full characterisation of both the ZnO and IZO layers are described in more detail in [14]. The transfer properties were a threshold voltage of  $-10\text{V}$ , a saturated field effect mobility in excess of  $10\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ , a switching ratio in excess of  $10^6$  and a sub-threshold slope of  $0.7 \text{ decV}^{-1}$ . The high threshold voltage is attributed to the thick dielectric layer used to define the transfer properties of these films.

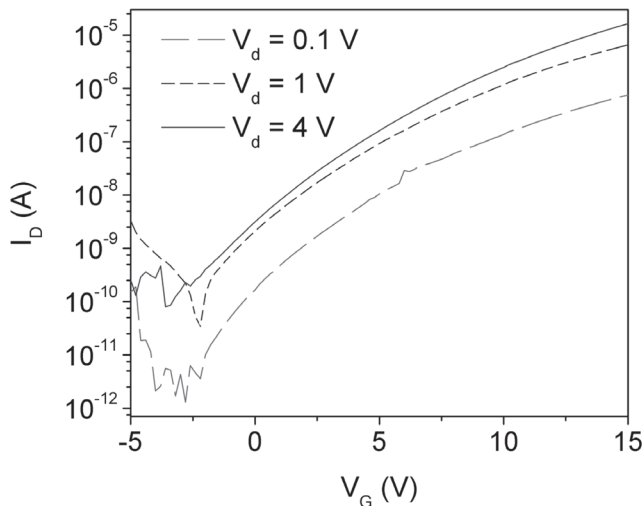


Figure 4: Transfer properties for hafnia/zinc oxide TFT devices.

## COMPLETE DEVICES

Complete devices were constructed using the HiTUS depositions of hafnia and ZnO described previously. For expediency, Corning 7059 glass substrates pre-coated 100 nm thick chromium bottom electrode were used. However, the HiTUS deposition technique can also be used for high quality indium tin oxide with resistivity  $<4 \times 10^{-4} \Omega\text{cm}$  at ambient temperatures [15]. A 100 nm thick layer of hafnia was then deposited using HiTUS. Transistor islands of low conductivity ZnO were then patterned onto the film using lift-off lithography. A second lift-off lithography step was then completed to define the source and drain contacts by coating with the conducting phase of the ZnO material. This ensured a high quality Ohmic contact between the top contacts and the semi-conducting channel layer. The transfer properties of this complete device structure are shown in Figure 4.

The transfer properties of the ZnO films are a threshold voltage of  $5.5\text{V}$ , a field effect mobility of  $0.2\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ , a switching ratio over  $10^4$  and a sub threshold slope of  $1.05 \text{ dec V}^{-1}$ . The reduced mobility of the ZnO compared to the IZO is attributed to the polycrystalline nature of these films compared to the amorphous structure of the IZO films.

## CONCLUSIONS

It has been shown that the HiTUS deposition technique can be used to deposit the critical layers required for the next generation of TFT devices. It is possible to deposit dielectric layers with high resistivity, high breakdown and hafnia with a dielectric constant  $\sim 23$ . Channel layers of ZnO and IZO demonstrate field effect mobilities of  $0.2\text{cm}^2\text{V}^{-1}\text{s}^{-1}$  and  $10\text{cm}^2\text{V}^{-1}\text{s}^{-1}$ . The wide process windows available for reactive depositions of these materials using the HiTUS technique provides a large control of the material properties, which in-turn enables high quality Ohmic contacts to be deposited onto the devices. Critically, these materials can be deposited at ambient process conditions enabling the potential for transparent electronics on plastics.

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