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Effects of e-beam deposited gate dielectric layers with atmospheric pressure plasma treatment for IGZO thin-film transistors

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In this report, indium gallium zinc oxide (IGZO) thin-film transistors (TFTs) performances were improved using atmospheric pressure plasma treatment on *e*-beam deposited silicon dioxide gate dielectric layers. The impact on the electrical properties of the IGZO-TFTs with different plasma powers at fixed N_2 gas flow rate on the SiO_2 dielectric surface has been investigated. The performances of the IGZO TFTs showed improvement at high power of 300 W and 400 W treatments. The amorphous IGZO films on SiO_2/ITO glass achieved transmittance higher than 90% in the wavelength range of 350–1000 nm, and it could be further enhanced with increasing plasma treatment power. The reduced surface roughness in the SiO_2 gate dielectric layer from increased plasma power would affect the performance of IGZO TFTs, especially by higher current on/off ratio, enhanced electron mobility, reduced sub-threshold swing voltage and interfacial trap charge density, and decreased threshold voltage. The amorphous IGZO TFTs with plasma treatment power at 400 W exhibited the field effect mobility, sub-threshold swing, on-current to off-current ratio, interfacial trap density and threshold voltage of 33.5 cm^2/V s, 0.10 V/dec, 10^7, 1.2×10^{12} cm^{-2} eV^{-1} and 0.77 V, respectively. In addition, the high mobility of 33.5 cm^2/V s was achieved using simple and cost-effective atmospheric pressure plasma treatment on e-beam deposited SiO_2 gate dielectrics.

1. Introduction

Transparent oxide semiconductor based thin-film transistors (TFT) have been the focus of immense interest as switching elements for flat panel display technology, such as active-matrix organic light-emitting diode (AMOLED) displays, active-matrix liquid crystal displays (AMLCD), and electronic papers [1–3]. They are highly desired for the next generation optoelectronic devices. Therefore, the transparent electronics received most prominent advantages because of their excellent capability in effectively producing wide range conductivity, good transparency in visual regime and high electrical mobility. In particular, the amorphous indium gallium zinc oxide (*a*-IGZO) has been justified as one of the most encouraging candidates among all transparent conducting oxide materials for TFT applications. It has high optical transmittance characteristics to fabricate high transparent TFTs, low-cost processing at low temperature in amorphous phase, and excellent surface morphology. Also, it has provided superior electrical properties, including high field-effect mobility, sharp sub-threshold swing, and high on/off current ratio as a channel material. These are very optimistic to those based on hydrogenated amorphous silicon (*a*-Si:H) [4], poly-Si [5], ZnO [6], In_2O_3 [7], IZO [8] thin-film transistors. Kuo et al. reported remarkable performance of *a*-IGZO based TFT for replacing the Si-based technology [9]. High surface morphology of amorphous phase films can be easily grown at low temperature on substrates with irrespective nature, such as silicon, glass and flexible plastics. The *a*-IGZO film has been used not only in TFT application but also as an alignment layer for liquid crystal display, which may integrate both in display technology in the future [10]. Recently, several physical vapor deposition methods have been used to grow *a*-IGZO films, including magnetron sputtering [11], and non-vacuum techniques such as atmospheric-pressure plasma jet [12], sol-gel [13], and ink-jet printing [14]. In this report, RF magnetron sputtering deposited *a*-IGZO film was used as a channel material for the TFTs application.

A suitable gate dielectric material is highly required to obtain high performance TFTs. Among all, silicon dioxide (SiO_2) was found as inherent gate dielectric material because of unique advantages such as thermo-dynamical and electrical stability, high quality interface state density, and electrical insulating properties. A high processing temperature would be required to grow SiO_2 film [15]. These methods have been found with certain disadvantages to be used on glass substrates because of the low softening point. Therefore, in this study, the SiO_2 dielectric layer deposition on glass substrate was carried out by an *e*-beam evaporator, because of the advantages in process simplicity at room temperature, cost effectiveness, and easy thickness monitoring over a large area [16]. The TFT electrical performance could be further improved by atmospheric pressure plasma treatment (APPT) on the e-beam deposited SiO_2 gate dielectrics. APPT has distinguished

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advantages such as improved adhesion, high reproducibility, short processing time, no drying stage, little energy consumption, and operation at near-ambient temperature, avoiding risk of heat exposure.

In this report, the IGZO TFT performances were improved using e-beam deposited SiO_2 gate dielectrics with APPT plasma treatment. The comparative performances of TFTs with different plasma treatment power at constant rate of nitrogen (N_2) gas flow on the SiO_2 surface were studied. The influence of treatment power on surface roughness, optical characteristics, atomic structure and electrical properties (capacitance) of SiO_2 film has been investigated. The mechanisms behind the improvement in electrical performance parameters such as field-effect mobility (μ_{fet}), ratio of the on-current to off-current (I_{on}/I_{off}), sub-threshold swing voltage (SS), interfacial trap charge density (N_{trap}) and threshold voltage (V_{th}) were thoroughly discussed. In addition, the high performance TFTs and good ohmic contact of source-drain on channel surface revealed that importance of plasma treatment on simple and low-cost e-beam deposited SiO_2 dielectrics in *a*-IGZO TFT applications. Also, it can employ the straight-forward device fabrication process in future display applications.

2. Experimental

Indium tin oxide (ITO) sputter-coated glass substrates have been used to fabricate the IGZO TFT devices. The sheet resistance of the ITO layer on glass was about 15 Ω/sq. The substrates were washed in acetone, alcohol and de-ionized water using ultrasonic agitation, and then dried by N_2 gun and 120 °C hotplate. The common bottom gate of ITO was defined from one side with covered shadow mask in the size of 1 mm × 20 mm. At First, these samples were deposited with SiO_2 gate dielectrics (200 nm) by an e-beam evaporator (ULVAC) using 99.99% SiO_2 source. Before the evaporation, the base pressure of the vacuum chamber was at 8×10^{-6} Torr (1.06×10^{-3} Pa), and it was increased to 4×10^{-5} Torr (5.3×10^{-3} Pa) during the SiO_2 film deposition. The steady deposition rate was about 3 nm/min. The distance between the source and the substrate was about 36 cm. Additional SiO_2 samples were prepared, also by e-beam evaporator on p^+ Si to evaluate the capacitance per unit area and bare glass for surface characteristics such as surface roughness, optical characteristics, etc. No substrate heating and/or post fabrication annealing was carried out. Some of the as-deposited samples required no plasma treatment and were used as the control samples. On the other hand, atmospheric pressure plasma treatment (NEMS-tek) was performed at power of 300 W (APPT 300 W) or 400 W (APPT 400 W) at N_2 gas flow rate of 50 L/min. The samples were attached on a moving table with a scanning speed of about 4 cm/s. The aligned plasma source had a fixed distance of 1 cm from the sample surface with an exposed duration of about 6 s. The IGZO semiconductor channel layers (40 nm) were then deposited on the bi-layer SiO_2/ITO glass using target (In:Ga:Zn = 2:2:1 atom.%; Tanaka Kikinzoku) by RF sputtering. The deposition power was 70 W. The chamber pressure was about 3×10^{-3} Torr (0.4 Pa). The Ar inlet gas flow rate was 50 sccm and the O_2 flow rate was 1 sccm. Finally, Al metallic film (100 nm) was coated by a thermal evaporator system. All samples were patterned to form the source and drain of IGZO TFTs, followed by photolithography and lift-off processes. The channel width was fixed at 1000 μm and the channel length was 200 μm. In addition, the IGZO films grown on glass were used for the investigation of physical characteristics such as optical transmittance (Jasco, ISN-723), X-ray diffraction analysis (XRD, BrukerD2 Phaser), X-ray photoelectron spectroscopy (XPS, VG Scientific Microlab 350), atomic force microscopy (AFM, Park System, XE-70). The top view of SiO_2 surface and TFT cross sectional image were examined by field-emission scanning electron microscopy (FE-SEM, Hitachi S-5000). A schematic illustration of the sample fabrication process and the device structure is shown in Fig.1. The TFT device electrical properties were evaluated at room temperature in dark environment using a semiconductor parameter analyzer (Agilent B1500A).

3. Results and discussion

The crystalline or amorphous structure of the SiO_2 gate dielectric layers deposited on glass was analyzed by XRD analysis. The same characteristics have been observed for the as-deposited films and the plasma-treated films. The SiO_2 films are likely amorphous or semi-crystalline by maintaining room temperature during film deposition using the e-beam evaporator method, as shown in Fig. 2. The prominent broadened peak at the angle of 24.3° was also originated from the existence of SiO_2 with orientation (222) in the glass substrates. The results agreed with the reported amorphous behavior of SiO_2 film deposited at room temperature [17]. The nature of film could be changed to crystalline properties by high temperature annealing treatment above 800 °C [18,19]. The power of plasma treatment did not influence the inner atomic structure of SiO_2 film and the film structure remained unchanged.

The effect of plasma treatment on the SiO_2 film surface characteristics was investigated using FESEM image analysis, shown in Fig. 3. The top-view images of the as-deposited and plasma-treated films at the power of 300 W and 400 W were all displayed. Apparently, the SiO_2 surface with the plasma treatment exhibited smoother film characteristics. It improved with increased power in the plasma treatment, indicating decreased defect properties on the surface after the plasma treatment. Moreover, the plasma treatment enhanced the quality of e-beam deposited SiO_2 film, also could be evidenced by the cross sectional images of TFTs. The cross sectional images of the IGZO TFTs with the as-deposited and 400 W plasma-treated SiO_2 gate dielectric were represented by Fig. 3(d) and Fig. 3(e), respectively. The plasma-treated sample showed prominent multi-layer structure with smoother and less defective SiO_2 film. The film also exhibited smoother surface in the interfacial region.

The surface morphology of the SiO_2 films has been investigated by atomic force microscopy. The AFM images of the as-deposited sample and the plasma-treated samples are shown in Fig. 4. The surface

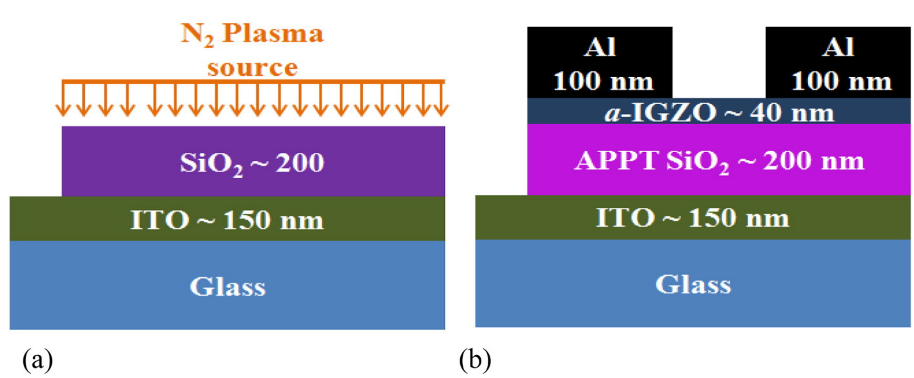

Fig. 1. Schematic illustration of (a) the plasma treatment process on SiO_2 film and (b) the sample structure of multi-layer TFTs.

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