Silicon-Oxide Thin Films Deposited by Plasma-Enhanced Atomic Layer Deposition for High Mobility Oxide TFT

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Abstract
Silicon oxide were deposited on the 6th generation glass by plasma-enhanced atomic layer deposition (PEALD). PEALD process proved to be an effective method to deposit robust thin films, suggesting its potential as a replacement for conventional passivation layers in high mobility oxide TFT process.

Author Keywords
Plasma-enhanced atomic layer deposition (PEALD); Silicon oxide; hydrogen; Large-area deposition

1. Introduction
Recently, commercialized indium-gallium-zinc-oxide (IGZO) based thin film transistors (TFTs) are attracting great interest due to their low leakage current and large area mass-production comparing with polycrystalline silicon (poly-Si) TFTs. However owing to low IGZO charge carrier mobility in comparison with poly-Si, indium-gallium-zinc-tin oxide (IGZTO) and indium-gallium oxide (IGO) have been proposed as an alternative material to meet the demand for high performance TFTs. A notable challenge with oxide TFT is their propensity to transition into conductive states in the presence of hydrogen [1], and this phenomenon is more pronounced in high mobility active layers such as IGZTO and IZO [2]. Hydrogen originating from gate insulator and passivation silicon oxide (SiOx) layers can diffuse into the active layer during post-processing and annealing, adversely affecting TFT reliability by altering the electrical properties of the active layer [3]. This issue poses a significant challenge in manufacturing high-performance display devices. To suppress the hydrogen penetration from gate insulator or passivation SiOx layers into the active layer, robust SiOx deposition processes are needed [4]. Traditional methods, such as plasma enhanced chemical vapor deposition (PECVD) have been employed for SiOx film deposition due to their relatively high deposition rates. However, PECVD is not an appropriate process in achieving the desired film quality, particularly concerning film density and step coverage. In contrast, plasma enhanced atomic layer deposition (PEALD) has gained attention for its superior step coverage and its ability to deposit SiOx films with reduced hydrogen content and increased film density [5]. Despite these advantages, the application of PEALD has predominantly been confined to semiconductor processes at wafer-scale dimensions. A significant obstacle to adopting PEALD in large-area display manufacturing is its inherently long deposition time, presenting a substantial challenge for high-throughput production.

In this study, we successfully deposited SiOx thin films on 6th-generation glass substrates using our PEALD equipment. By implementing continuous reactant and purge gas flows, we optimized the ALD cycle time and achieved uniform thin film thickness. Furthermore, we demonstrate that SiOx thin films by PEALD exhibit superior film density and effectively suppress the release of hydrogen and H_2O gases from the deposited film.

2. Experimental
SiOx thin films were grown on the 6th-generation glass substrates using a PEALD system. High-purity argon was utilized as both the carrier and purge gas while Diisoprophylaminosilane (DIPAS) was employed as the silicon precursor, delivered via a liquid delivery system. Nitrous oxide (N_2O) served as the oxygen reactant source. To prevent vapor-phase reactions between the N_2O and the silicon precursor, a short purge time was implanted immediately after the surface adsorption of silicon precursor. In conventional PEALD processes, purging is conducted following both precursor dosing and reactant plasma exposure [6]. However, in this study, purging was performed only after DIPAS dosing. Argon gas and N_2O reactant gas were introduced continuously into chamber to reduce the overall process cycle time. This modified sequence resulted in a process cycle time reduction of over 25% compared to previously reported methods. The specific PEALD sequence of SiOx deposition was illustrated in Figure 1. To examine the influence of substrate temperature on film properties, depositions were performed at 250°C and 350°C. These temperatures were chosen to evaluate the material quality of the SiOx films. The density of the SiOx films was measured by X-ray reflectivity (XRR) with Cu Kα radiation. The refractive index was determined by spectroscopic ellipsometry. The release of hydrogen and H_2O molecules from the deposited films was assessed using thermal desorption spectroscopy (TDS).

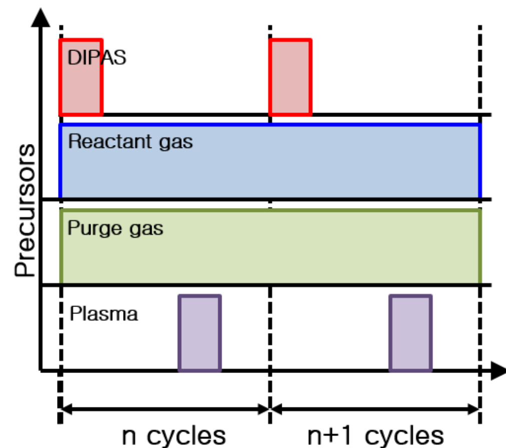

Figure 1. Sequence of PEALD SiOx deposition cycles

3. Results and discussion
The growth per cycle (GPC) of PEALD SiOx films was investigated by varying the exposure time of DIPAS precursor, purging time after DIPAS dosing, N_2O plasma exposure time, and N_2O rf power. Self-limited GPC was achieved under the following conditions; DIPAS exposure time >0.3 seconds, purging time after DIPAS dosing ≥0.8 seconds, plasma exposure time ≥0.7 seconds, and rf power ≥5kw rf power (Fig.2). Under

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these deposition saturation conditions, the GPC was measured to exceed 0.9Å/second, and the thickness uniformity of the SiOx films on 6th-generation glass substrates was determined to be approximately 2%.

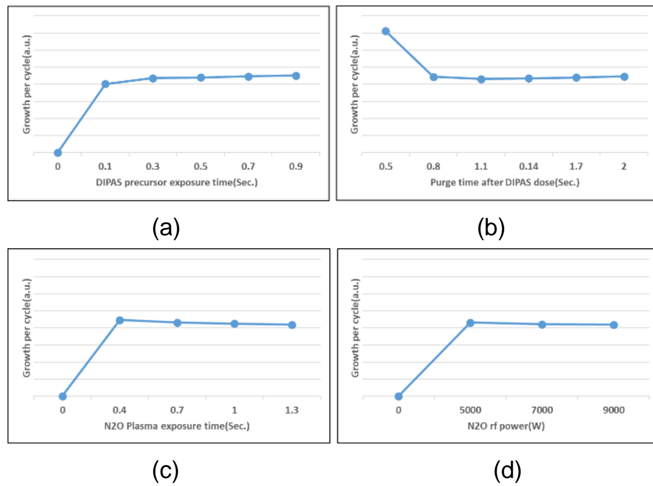


Figure 2. Self-limiting growth behavior depending on (a) DIPAS exposure time (b) purging time after DIPAS dose (c) N_2O plasma exposure time (d) N_2O rf power

TEM analysis was performed to evaluate the step coverage of the SiOx films, a key indicator of the effectiveness of the ALD process. Figure 3 demonstrates the superior conformality (≥95%) of the SiOx films deposited by PEALD, confirming the process capability to achieve uniform deposition even on complex surface geometries.

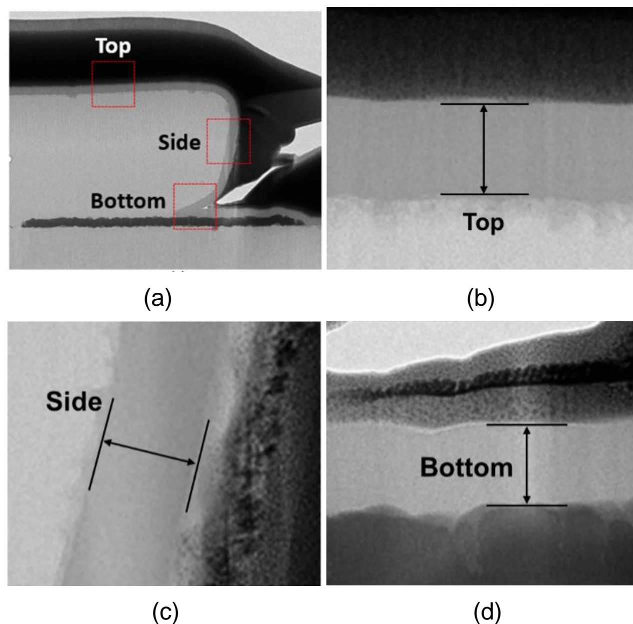


Figure 3. HRTEM images of silicon oxide thin films are shown in cross-sectional view with (a) HRTEM image with lower magnification (b) top end of deposited SiOx (c) side end of deposited SiOx (d) bottom end of deposited SiOx.

To compare the properties of SiOx thin films deposited by PEALD and PECVD (reference), refractive index and film density were measured under varying deposition conditions, including electrode spacing (8.9mm and 15.2mm) and deposition temperature (250°C and 350°C), as shown in Figure 4. While the refractive index remained constant irrespective of process conditions, the density of PEALD-grown films was 4~5% higher than that of the reference film. This higher density can be attributed to the sequential atomic layer deposition through self-limiting reactions inherent to the PEALD process, resulting in denser structure with minimal micro-pores.

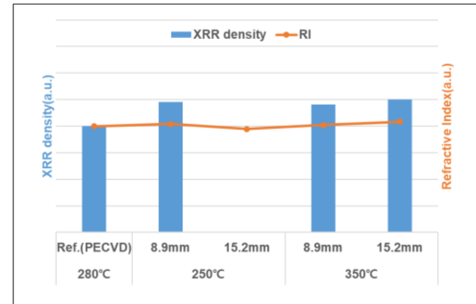


Figure 4. XRR film density and refractive of silicon oxide thin films deposited by the reference PECVD and PEALD under varying electrode spacings and deposition temperatures.

TDS was used to evaluate the release of hydrogen and water molecules from the films. As shown in Figure 5, SiOx films deposited by PEALD released significantly lower amounts compared to those deposited by PECVD, except for films deposited at 250°C with 8.9mm electrode spacing. The released hydrogen and water content decreased further under conditions of higher deposition temperature and wider electrode spacing. The reduced hydrogen release in PEALD films is primarily linked to their higher density. However, additional factors beyond density were identified as influential, as the XRR measured densities of all PEALD films were similar. Electrode spacing was identified as a critical factor influencing plasma parameters such as electron temperature and electron density. It is considered the effect of increasing power loss area within plasma according to the power balance equation, which is given by

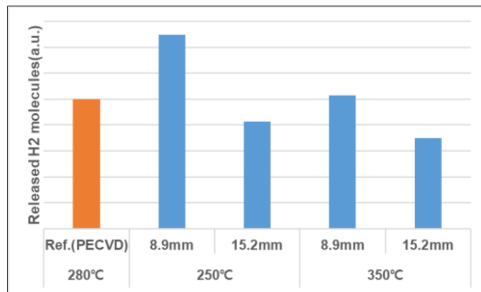
$$n_0 = \frac{P_{abs}}{e u_B A_{eff} \epsilon_T} \quad (1)$$

where n_o is the electron density, P_{abs} is the absorbed power, e is the elementary charge, u_B is the bohm velocity, A_{eff} is the effective area for particle loss and ϵ_T is the total energy lost power electron-ion pair.

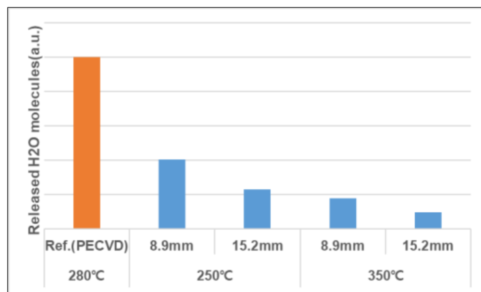
$$\frac{K_{iz}(T_e)}{u_B(T_e)} = \frac{1}{n_g d_{eff}} \quad (2)$$

Where K_{iz} (T_e) is the rate constant of ionization, n_g is the neutral density, and d_{eff} is the effective plasma size. Increasing electrode spacing expends A_{eff} and d_{eff}, leading to a decrease in electron density and electron temperature. Ion density is similar with electron density due to plasma quasi-neutral property. Simultaneously, the sheath potential increases with electron temperature, enhancing ion acceleration energy. Consequently, narrower electrode spacing results in a higher ion flux to the substrate. It is well-documented that higher ion flux can induce defects in thin films, negatively impacting hydrogen release properties [7]. Wider electrode spacing can minimize ion

bombardment damage, making it essential for PEALD SiOx deposition. Furthermore, higher deposition temperatures can effectively anneal defects cause by ion bombardment. Under the condition of 350℃ deposition temperature and 15.2mm electrode spacing, the hydrogen and water release values were reduced by approximately 30% and 90% respectively, comparing with the film deposited by PECVD. This significant improvement shows the importance of controlling both electrode spacing and deposition temperature in achieving high-quality, low-defect SiOx films for advanced applications.



(a)



(b)

Figure 5. Thermal desorption data of (a) H_2 molecules and (b) H_2O molecules released from silicon oxide thin films deposited by reference PECVD and PEALD under varying electrode spacings and deposition temperatures.

4. Conclusion

Silicon oxide thin films were successfully deposited on the 6th-generation glass substrate using the PEALD process. Self-limiting growth characteristic was maintained even with continuous reactant gas and purge gas flows, significantly reducing the takt time. The density of thin films fabricated by PEALD is 4~5% higher than those deposited by PECVD. By controlling electrode spacing and deposition temperature, hydrogen and water release were reduced by 30% and 90%, respectively, compared to PECVD films. The PEALD process was demonstrated as an effective method to deposit robust thin films, making it a promising alternative for conventional gate insulator and passivation layer in high-mobility oxide TFT application.

5. References

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