ALD Applications
Room Van Rysselberghe - Session AA1-TuA
ALD for Display Applications

Moderators: Jin-Seong Park, Hanyang University, Ganesh Sundaram, Veeco-CNT

1:30pm **AA1-TuA-1 Atomic Layer Deposition for Display from Photoluminescent Materials to Devices and Encapsulation***, **Rong Chen**,* State Key Laboratory of Digital Manufacturing Equipment and Technology, School of Mechanical Science and Engineering, China **INVITED**

As display plays an increasingly important role, from mobile phones, display screens, to AR/VR and metaverse glasses. There are increasing demands for pursuing more vivid displays, requiring higher resolution, wider color gamut with high stability. Atomic layer deposition (ALD) has been developed as an attractive method to modify and stabilize the photoluminescence materials and devices.[1] In this presentation, several applications through ALD are introduced. For photoluminescence (PL) applications, ALD is performed to coat dense layer on fluoresce materials and passivate defects. For example, Al_2O_3 coating on RLSO:Eu^{2+} phosphor demonstrates outstanding moisture resistance and PL stability.[2] For quantum dots, low-temperature plasma enhanced ALD is developed to enhance the stability of $CsPbBr_3$ QDs films in light, water and heat, which originated from the crystal stabilization after coating.[3-5] Ultra-stable luminescent microspheres structures are fabricated to confine QDs with SiO_2 sphere to improve stability for backlight display.[6] In terms of light-emitting diode (LED), ALD is exploited to infill oxides between QDs, improving the carrier mobility.[7,8] The ultrathin functional layers prepared with ALD could effectively balance the carrier and block the migration of metal ions from the electrode to the functional layers to avoid device damage.[9] For flexible encapsulation, ALD plays an important role for OLED, QLED and micro-LED etc.,[9] inorganic-organic composite layers, nanolaminated packaging structures with total thickness of 100 nm are fabricated as encapsulation layer and significantly improve mechanical stability under bending and stretching tests.[10] The atomic layer infiltration (ALI) has been developed to prepare hybrid organic-inorganic layers with better flexibility.[11,12] Our works provide a versatile method for LED illumination and flexible displays, it is also beneficial to fabricate oxides with high mobility (ZnO, IGZO etc.) for TFT, in the future, the manufacturing equipments (spatial ALD, particle ALD) with mass production capability are also urgent needed for commercial applications.

References

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[2]*Angewandte Chemie International Edition***2020**, *59*, 12938.

[3]*Chemistry of Materials***2018**, *30*, 8486.

[4]*ACS Appl Mater Interfaces***2020**, *12*, 53519.

[5]*Chemistry of Materials***2020**, *32*, 10653.

[6]*Advanced Optical Materials***2020**, *8*, 1902118.

[7]*physica status solidi (RRL)* **2020**, *14*, 2000083.

[8]*ACS Applied Electronic Materials***2021**, *3*, 2398.

[9]*Advanced Materials Interfaces***2020**, *7*, 2000237.

[10]*Advanced Materials Interfaces***2021**, *8*, 2100872.

[11]*Dalton Trans***2021**, *50*, 16166.

[12]*Advanced Materials Interfaces***2022**, 2101857.

2:00pm **AA1-TuA-3 High-Stability and High-Performance PEALD-IZO/IGZO Top-Gate Thin-Film Transistor via Nano-Scale Thickness Control***, J. Park, **Yoon-Seo Kim**, W. Lee, H. Oh, T. Hong,* Hanyang University, Korea

Oxide semiconductors have already been adopted for mass-production of display backpanes because of their advantages of high field effect mobility (10~30 cm^2/Vs), large-area uniformity, low-cost manufacturing and low-temperature process. The next generation of display technology such as super high vision and memory/logic technology requires the semiconductor which has electron mobility higher than 30 cm^2/Vs with high stability. In addition, for application in 3D structures such as 3D NAND, uniform thickness and composition control in 3D structures are required. Therefore, further than the conventional PVD method, it is necessary to study ALD-based oxide semiconductors that can control the thickness of an atomic level and form a film with low defects based on self-limit reaction. Furthermore, the ALD method facilitates the development of high-performance oxide semiconductors by controlling the homogeneous/heterogeneous vertical structure and composition. Therefore, ALD is suitable as a powerful deposition method candidate for oxide semiconductor development. However, since most research of stacking oxide semiconductor which is the methods to overcome the mobility and reliability trade-off is based on sputter or solution deposition, the ALD-based oxide semiconductor stack studies have rarely been reported. In this study, PEALD-based IZO (back-channel)/IGZO top gate thin film transistor investigated relation between the thickness of the IZO layer and electrical/reliability properties of devices. The mobility increases proportionally according to the IZO thickness. In addition, the PBTS reliability is excellent with an absolute value ΔV_{th} of less than 0.4 V in all of PEALD based TG-TFTs. In particular, the reliability of PBTS is improved proportionally according to the IZO thickness in IZO/IGZO TFT compared to IGZO TFT. Finally, we fabricated PEALD IZO/IGZO TG-TFTs with high mobility (~40 cm^2/Vs) and high stability of PBTS under 10800 s (ΔV_{th} = -0.07 V) through nano scale thickness control.

2:15pm **AA1-TuA-4 Atomic Layer Infiltration Enabled Flexible Encapsulations***, **Fan Yang**, Y. Zhang, D. Wen, K. Cao,* State Key Laboratory of Digital Manufacturing Equipment and Technology, School of Mechanical Science and Engineering, Huazhong University of Science and Technology, China*; R. Chen,* State Key Laboratory of Digital Manufacturing Equipment and Technology, School of Mechanical Science and Engineering, Huazhong University of Science and Technology , China

Due to the, low-cost, large area, light weight, high transparency and high flexibility, polymer based thin-film encapsulation (TFE) and substrates have emerged as one of the most attractive methods for flexible electronics hermetic sealings. However, the intrinsic barrier performances of various polymeric substrates are still too low to prevent moisture and oxygen in an ambient atmosphere to permeate into and degrade the protected devices at its static state, not even mention when at bending or stretching. Different novel configurations, such as wrinkled structures, island-bridge, serpentine structure, origami structure, and helical coil, have been developed to improve the flexibility of polymer FTEs, while at the cost of either low device-coverage density or low transparency. Therefore, effective method and the underlying modification mechanism are in desperate desire for polymer TFEs with high stretchability, excellent transparency, and good barrier property.

In our work, different polymer substrates including polydimethylsiloxane (PDMS) and commercial polyethylene naphthalate (PEN), are modified with atomic layer infiltration (ALI) method. A clear “nucleation-filling-coating” modification mechanism is proposed and elaborated in detail by in-situ quartz crystal microbalance (QCM). The optimized PDMS and PEN hybrid films both exhibit relatively low water vapor transmission rate (WVTR) values and excellent mechanical reliability under bending or stretching conditions. Moreover, patterned sensitive quantum dots (QDs) and based devices encapsulated with the modified hybrid polymer films retain outstanding performances and lifetimes, comparing with ones protected with unmodified polymers. We believe the proposed ALI modification and mechanism will have great and practical implications for encapsulations for future flexible electronics.

References:

1, Highly-stable PEN as a gas-barrier substrate for flexible displays via atomic layer infiltration. Yun Li, Di Wen, Yinghao Zhang, Yuan Lin, Kun Cao, Fan Yang and Rong Chen,*Dalton Trans.,* ***2021****, 50, 16166.*

2, Stretchable PDMS Encapsulation via SiO2 Doping and Atomic Layer Infiltration for Flexible Displays. Yinghao Zhang, Di Wen, Mengjia Liu, Yun Li, Yuan Lin, Kun Cao, Fan Yang, and Rong Chen, *Adv. Mater. Interfaces* ***2021****, 2101857*

2:30pm **AA1-TuA-5 Impacts of Deposition Temperatures on Insulation Properties of Atmospheric Pressure Spatial ALD Al_2O_3 Thin Films for Flexible PEALD IGZO TFT***, **Dong-Gyu Kim**, K. Yoo, S. Lee, W. Lee, J. Park,* Hanyang University, Korea

In the past decades, aluminum oxide (Al_2O_3) has attracted attention because its unique properties such as a wide band gap (~9 eV), a reasonable breakdown electric field (5-10 MV/cm), excellent dielectric properties (6–9), strong adhesion to various materials, and high thermal/chemical stability. There are various Al_2O_3 deposition methods. Among them, atomic layer deposition (ALD) is regarded as a promising conformal film deposition tool. Although ALD-derived Al_2O_3 films have abundant advantages, the ALD method is not always compatible with industrial needs because of its extremely low growth rate (0.1 nm/s). Therefore, many groups have suggested spatially separated ALD (S-ALD) concept to increase growth rate for mass production. In the S-ALD operation, both precursor and reactant are continuously injected and purged from different zones. A moving substrate crosses each zone for chemical reactions between the adsorbed precursor and reactant, and the time-consuming purge steps are no longer needed. Meanwhile, as market demand increases for flexible display, several researchers developed the S-ALD method that works at atmospheric pressure (AP S-ALD). These include roll-to-roll/sheet-to-sheet processes and low investment costs. Although the AP S-ALD have gained increasing interest, the AP S-ALD-derived Al_2O_3 film properties have not clearly observed as a function of deposition temperatures to date. Furthermore, the possible applications of the oxide-based thin film transistors (TFTs) as an insulator should be evaluated.

In this work, we report AP S-ALD-derived Al_2O_3 growth behaviors with different process parameters. For more in-depth growth temperature studies, we conducted X-ray reflectometry (XRR), X-ray photoelectron spectroscopy (XPS), and atomic force microscopy (AFM) analyses. We fabricated metal-insulator-metal (MIM) devices to evaluate the dielectric constant and breakdown electric field. Based upon results, we used the optimal Al_2O_3 as a B.L and G.I to investigate the application in PEALD IGZO TFT. We evaluated instability of the IGZO TFT as a function of gate field stress time and mechanical bending cycle number to understand the Al_2O_3-adopted PEALD-IGZO TFT flexible display.

2:45pm **AA1-TuA-6 Enhanced Crystallinity Using in-Situ Atomic Layer Deposition Process of Al_2O_3 on P-Type SnO Thin Film and the Associated Device Applications***, **Hye-Mi Kim**, S. Choi, J. Park,* Hanyang University, Korea

Tin monoxide (SnO) is promising p-type material which have low formation energy of tin vacancy (V_{Sn}) and high hole mobility arise from the delocalization of hole conduction path. However, low thermal stability of p-type SnO and facile phase transition to n-type tin dioxide (SnO_2) is major hardship to achieve superior electrical properties and stability[1,2]. In this study, we focused on the effect of Al_2O_3 on SnO film properties especially on the crystal structure and electrical performance. Al_2O_3 is already known for effective materials for the passivation layer of SnO TFT in many reports. However, we figured out that $Al_2O\text{-}_3$ not only passivate the surface defect of SnO but also highly influence on the crystallinity and following electrical properties. Also, this effect is enhanced when Al_2O_3 is deposited as in-situ ALD process. To identify the mechanism of the improvement of crystallinity, the nucleation energy and the chemical potential difference of SnO and Al_2O_3 stacked SnO crystallites is calculated. SnO TFT with in-situ processed Al_2O_3 exhibits 1.14 cm^2/Vs of field-effect mobility, 4.4E+05 of on/off ratio and low subthreshold swing as 0.15 V/decade. Our study confirms that the mechanism of the improvement in electrical performance of SnO TFT when Al_2O_3 passivation layer is adopted, and in-situ process is far more effective to achieve high performance.

References

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(2) Luo, H.; Liang, L. Y.; Cao, H. T.; Liu, Z. M.; Zhuge, F.Structural, Chemical, Optical, and Electrical Evolution of SnO x Films Deposited by Reactive Rf Magnetron Sputtering. ACS Appl. Mater. Interfaces 2012, 4 (10), 5673−5677

3:00pm **AA1-TuA-7 Oxidant- and Temperature-Dependent Growth Behavior of ALD-Processed ZnO Thin Films and their Applications inTransistors***, J. Yang, A. Bahrami, **Sebastian Lehmann**, S. He, N. Kornelius,* Leibniz Institute for Solid State and Materials Research, Germany

ZnO thin films were deposited by atomic layer deposition (ALD) using diethylzinc (DEZ) as the Zn source and H_2O and H_2O_2 as oxygen sources. The oxidant- and temperature-dependent electrical properties and growth characteristicsare systematically investigated. Materials analysis results suggest that H_2O_2 provides an oxygen-rich environment so that the oxygen vacancies (V_O) is suppressed, implying a lower carrier concentration and a higher resistivity. The lower growth rate makes it possible for the ZnO thin films to grow along the lower surface energy direction of <002>, leading to a lower Hall mobility. Furthermore, the ZnO semiconductor was integrated into thin film transistor (TFT) devices, and the electrical properties are analyzed. The TFT with H_2O_2-ZnO grown at 150 °C shows good electrical properties, such as a high field-effect mobility of 10.7 cm^2 V^{-1} s^{-1}, a high ratio I_{on}/I_{off} of 2×10^7, a sharp subthreshold swing (*SS*) of 0.25 V dec.$^{-1}$, and a low trapping state (N_{trap}) of 2.77×10^{12} eV^{-1} cm^{-2}, which provides a new pathway to optimize the performance of metal-oxide electronics.

3:15pm **AA1-TuA-8 Origins of High Off-current of P-type SnO TFTs and Reduction by Source/drain Modulation***, **Su-Hwan Choi**, H. Kim, J. Park,* Hanyang University, Korea (Republic of)

Tin monoxide (SnO) is a promising material for p-type thin-film transistors (TFTs) due to its high hole mobility because SnO forms a delocalized and isotropic hole conduction path with hybridized spherical Sn 5s orbitals and O 2p orbital. However, SnO TFTs have a high off-current because of their ambipolar characteristics, which operate n-type mode at back-channel. The high off-current is undesirable for low power consumption and high CMOS gain. High off current originates from a redox reaction [1], oxygen vacancy generation of SnO [2], and electron injection through source/drain [3] In this study, the origin of the high off-current for P-type SnO thin-film transistor (TFT) is examined by source/drain (S/D) electrode materials. The electrical properties of Ni electrode TFT are superior to the ITO electrode TFT in terms of mobility. However, Ni electrode TFT has a high off-current originating from redox reaction and electron injection through Ni electrode. The ITO interfacial layers (ILs) are adopted to reduce the off-current by restraining the redox reaction and electron injection. For 10nm ITO ILs TFT, optimum electrical properties are achieved, such as field-effect mobility of 2.5 cm2/Vs, a threshold voltage of -1.9 V, a subthreshold swing of 0.43 V/decade, and especially high Ion/Ioff of 1.7×103. Reference : [1] H. Luo, L. Y. Liang, H. T. Cao, Z. M. Liu, and F. Zhuge, "Structural, Chemical, Optical, and Electrical Evolution of SnO," 2012. [2] J. M. Chem, J. P. Allen, D. O. Scanlon, F. J. Piper, and G. W. Watson, "Journal of Materials Chemistry C," pp. 8194–8208, 2013, doi: 10.1039/c3tc31863j. [3] L. Y. Liang, H. T. Cao, B. Chen, Z. M. Liu, F. Zhuge, and H. Luo, "Ambipolar inverters using SnO thin-film transistors with balanced electron and hole mobilities," vol. 263502, pp. 1–5, 2012.

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