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◆ 특집 ◆ 인쇄전자 공정장비기술

플렉시블 디스플레이용 박막 도포를 위한 초정밀 슬롯다이 코팅장비

High-Precision Slot-Die Coating Machine for Thin Films of Flexible Display

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We developed a compact high-precision slot-die coating machine for thin-film deposition on a flexible substrate. For smooth and precise coating, air-bearing and linear motor system were employed to minimize velocity ripple. The gap control mechanism is specially designed to have repeatability of gap between nozzle and substrate under 1 μm. Due to extremely precise gap control, the machine can coat thin-films down to 50 nm with 200 mm × 100mm size. A thin film of Ag nano-particle ink is coated for demonstration.

Key Words: Slot Die Coating (슬롯다이코팅), Velocity Control (속도제어), Precision Machine (정밀기계)

1. Introduction

Slot-die coating is a promising technology for thin-film deposition on flexible substrates. It provides pre-metered coating to obtain a desired film thickness without wasting coating materials. Also, the coating material is not exposed to the air until it is deposited. The slot-die coating process has several advantages over conventional coating methods like spin coating. First, it can be used for large-format displays. Second, it can coat thin-film over non-smooth surfaces like TFT backplanes.[1]

The quality of the coated film is largely affected by process parameters such as pumped flow rate, coating speed, liquid properties, geometry of the die and a gap between the coating die and the substrate.[2] The combination of these parameters to have defect-free coating is called "coating window".[3] Usually, coating window can be determined by separating stable and unstable regions in the space of the process parameters such as coating speed and the gap. In the unstable region, the defects which is generally called as rivulets can be found. There have been several previous studies to analyze the coating window and to find a maximum coating speed and a minimum film thickness with given coating parameters.[4-9] Carvalho & Kheshgi[8] found a formula for low-flow limit using the viscocapillary model. The formula is shown as following

$$Ca = \frac{\mu V}{\sigma} = 0.65\left(\frac{2}{\left(H_0/t\right)-1}\right) \tag{1}$$

where Ca is Capillary number, μ is liquid viscosity, V is coating speed, σ is surface tension coefficient, H_0 is the gap between the coating die and the substrate, t is wet thickness of liquid film. Eq. (1) means that, as the coating speed (V) increases and the wet thickness (t) decreases, the maximum gap for low-flow limit should decrease for stable and uniform coating quality. If we want to coat very thin film with high coating speed, we have to minimize the gap without damage of coating die by the contact to the substrate.

In this paper, we developed a lab-scale high-precision slot-die coating machine. Slot-die coating process is usually used as a roll-to-roll based system, which requires big footprint and high cost.[10] Sheet-fed slot-die coating is simple and easy method to test thin-film coating of expensive functional materials. For high coating quality of very thin-film, we precisely controlled the coating speed and the gap between slot-die nozzle and substrate by using high-precision actuators and sensors.

2. Slot-Die Coating Machine

2.1 Design

Fig. 1 shows a design layout of the proposed high-precision slot-die coating machine. It has a C-shaped granite frame that the nozzle is fixed at the upper part and the air-bearing stage moves under the nozzle. The substrate is fixed on the finely polished granite vacuum chuck that is carried by the air-bearing stage. During coating, the air-bearing stage moves with a constant speed. To obtain uniform coating, the moving speed should be controlled with extreme accuracy. Our machine uses a coreless-type linear motor to provide ripple-free motion and air-bearings to eliminate friction. The slot-die nozzle is attached to a specially designed tilting mechanism that adjust the height and tilt angle of the nozzle with sub-micrometer accuracy. All the moving parts have their own linear scales to improve positioning accuracy.

With the help of origin calibration sensors aligned to the surface of the flat chuck, the nozzle can travel over the substrate with a known coating gap. To make sure that the nozzle moves above the substrate with certain height, we need to calibrate the origin of the slot-die nozzle. First, high precision the displacement sensor is located right under the nozzle. And a flat block polished with sub-micrometer flatness is put to cover both the sensor and the chuck. At this time, we record the sensor output as a reference. Finally, the nozzle approaches pushing down the sensor until the sensor output reaches the reference. Once the reference is touched, the positions from the linear scale of the Z actuators are recorded as origin positions.

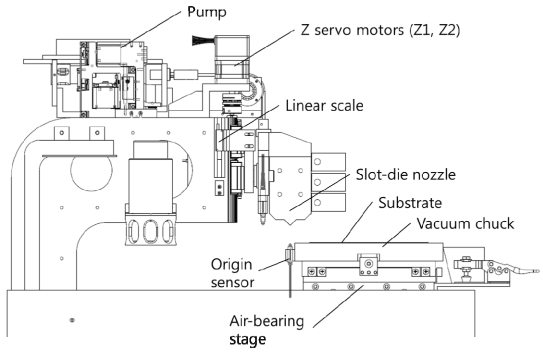

Fig. 1 Design layout of high-precision slot-die coating machine

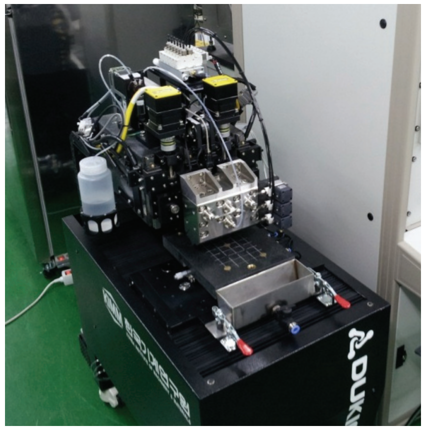

Fig. 2 High-precision slot-die coating machine

The manufactured slot-die coating machine is shown in Fig. 2. The size is about 400 mm × 750 mm × 1500 mm. An active coating area is up to 200 mm × 100 mm. The slot-die machine has an automated pumping and venting system. A syringe pump provides solution into the slot-die nozzle. The nozzle has three ventilation outlets and each outlet has a solenoid valve. Pump rates is synchronized with the motion of the substrate and the nozzle.

2.2 Coating process

The slot-die coating is a pre-metered coating method. We can estimate the thickness of wet coated film from

Fig. 3 Coating process of the sheet-fed slot die coating machine

total volume of pumped ink, coating width and coating length. But the pump rate and the substrate speed may vary according to ink properties. Contrast to roll-to-roll slot-die coating, our machine coats solution onto a sheet substrate. At the start and end of coating process, coating thickness depends on the response of the pump. Thus, transient control of the pump is very important for entire uniformity.

The slot-die coating process on a sheet is performed as shown in Fig. 3. At first, bleeding is to fill the slot perfectly. Then, excess ink is swiped out from the nip of the nozzle for clean coating bead creation using pre-dispensing. At the end of the coating, the ink is sucked back into the nozzle for clear finish. To make a uniform thin-film, the parameters of each step should be tuned finely. Except ink properties, the important parameters are considered as pre-dispensing amount, coating speed, coating gap, and flow rate of pump.

3. Experimental Results

3.1 Velocity ripple

During coating, the velocity ripple of the moving substrate cause uneven amount of ink in the moving direction. Especially with high viscosity ink, the coated film may have wavy surface. The controller for the air-bearing stage is tuned carefully to have high tracking performance for a constant velocity. Fig. 4 shows the velocity ripple of the air-bearing stage when the stage moves in 10 mm/s and 100 mm/s. The velocity ripples were recorded with the sampling frequency of 905 Hz. At 10 mm/s and 100 mm/s, the velocity ripple was 0.25%(3σ) and 0.05%(3σ), respectively. Even at the very low speed, the air-bearing stage shows good tracking performance without experiencing any frictional behavior or periodic ripples. The extremely small velocity ripple helps acquire uniform coating thickness without any waviness.

3.2 Gap control

To show the accuracy of the origin calibration

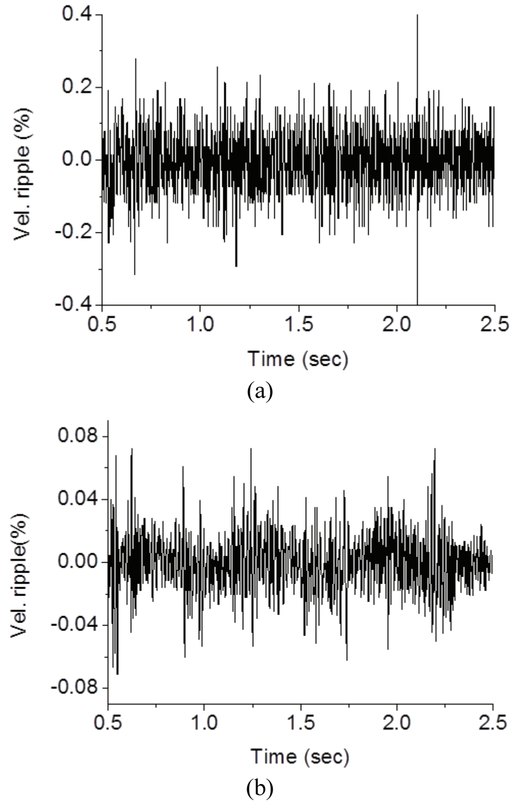

Fig. 4 Velocity ripple at (a) 10 mm/s (b) 100 mm/s

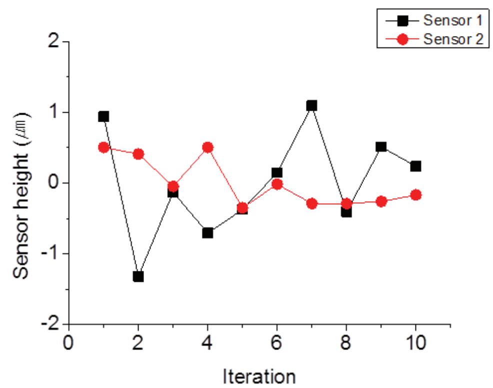

Fig. 5 Sensor repeatability by loading the flat block

accuracy, the displacement sensors and the calibration algorithm were examined. First, we checked the sensor reading when we load the flat block. For 10 times of loading, a standard deviation of 0.25 ㎛ was obtained as shown in Fig. 5. It means that the sensors indicate repeatable heights whenever we load the flat block. Next,

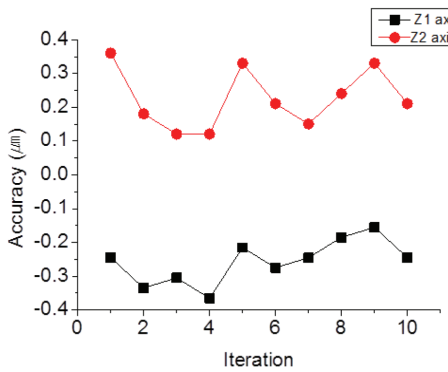

Fig. 6 Origin search accuracy

once we load the flat block and record the sensor heights, the origin search was repeated 10 times. The searched positions of both z-axes are shown in Fig. 6. Z1 axis and Z2 axis show a mean error of 0.26 ㎛ and 0.23 ㎛, and a standard deviation of 0.062 ㎛ and 0.084 ㎛, respectively. Thus, we may conclude that the origin calibration process has an accuracy less than 1 ㎛. With this highly precision gap control, we can minimize the gap below 5 ㎛ for very thin film coating with high speed.

3.3 Slot-die coating

To test the slot-die coating machine, we coated Ag nano-particle ink (reverse-offset ink 39wt% of Ag, Advance Nano Products Co.) on a 250 mm × 150 mm glass substrate. Fig. 7 shows the picture of the coated Ag thin-film. The wet thickness was about 16.7 ㎛ with the coating speed of 50 mm/s and the coating gap of 30 ㎛. After coating, the glass substrate was dried at 180 ℃ for 60 minutes in a furnace. To check the uniformity of the coating, the dried film thickness was measured at 25 points over 160 mm by 80 mm using 3D profilometer (P-6, KLA Tencor). Fig. 8 shows the uniformity map of the measured points. The averaged film thickness was 0.624 ㎛ and the standard deviation was 4.36 % of the averaged film thickness. The uneven thickness results from the different evaporation speed of solvents in the ink.

4. Conclusions

We developed a lab-scale high-precision slot-die coating machine for thin-film deposition. To achieve a high-precision coating machine, two features are considered in design. The air-bearing stage assures smooth and precise motion of the substrate with the velocity ripple less than 0.08 % rms. The automatic origin calibration system enables the nozzle gap down to 5 ㎛. We successfully demonstrated a thin-film coating which has an averaged film thickness of 624 nm with 4.36 % uniformity. It can be used for quick evaluation of various flexible electronics applications such as flexible displays, solar cells, touch screen panels and transparent conductive film.

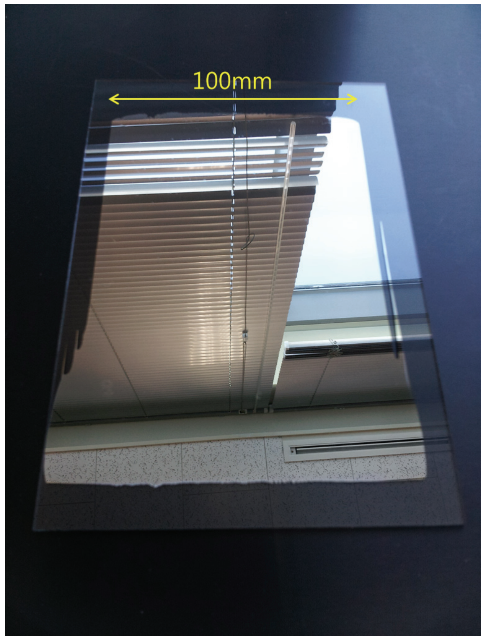

Fig. 7 Coated silver thin-film

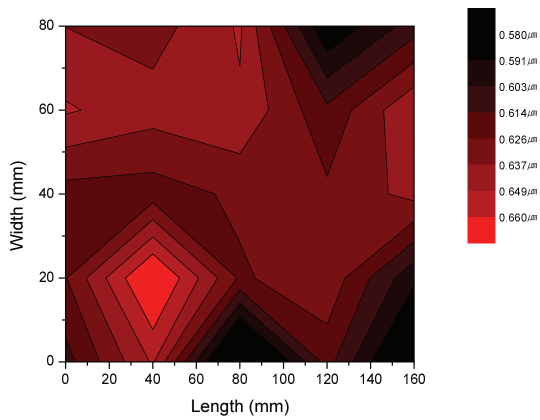

Fig. 8 Film thickness of slot-die coated Ag ink

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