Mechanical Debonding for Flexible Display Production

Ha Young Lee[1], Chansoo Kim[1], Sun Woo Park[1], Dongwook Lee[1,*]
dongwook@hongik.ac.kr
[1]Department of Materials Science and Engineering, Hongik University, Seoul 04066, Republic of Korea
Keywords: Flexible display production, Mechanical debonding, Debonding layer, 2D materials

ABSTRACT

The mass production of flexible display currently relies on laser-based liftoff (LLO) process, where bonding between the carrier glass and flexible polyimide (PI) substrate is removed by laser. However, LLO process accompanies degradation at the bottom surface of the PI substrate and is sensitive to particulates. Here, we report a 2D material-based debonding layer for non-laser-based mechanical liftoff process. We demonstrate that debonding force can be lowered from 17.69 gf/in (PI – carrier glass) to 1.50 gf/in (PI – the debonding layer – carrier glass), which surpasses the 5 gf/in industry target for practical liftoff process. This 91.5 % decrease in debonding force is realized by (i) weak bonding forces of PI – debonding layer and debonding layer – carrier glass pairs, along with (ii) the 100 % coating coverage of the debonding layer preventing the direct bonding of the PI – carrier glass pair. This novel liftoff technology can be a competent low-cost and non-damaging solution for flexible display production.

1 Introduction

Currently, the flexible PI substrate is the main substrate for flexible displays. During the manufacturing processes, the position of the PI is fixed on a carrier glass substrate to prevent deviation of the PI substrate during position-sensitive processes. However, at the end of the production processes, a lift-off process to separate the lower surface of the PI from the carrier glass is essential. This corresponds to LLO, during which the lower surface of the PI attached to the carrier glass substrate is damaged. So far drawbacks of LLO include (i) need for expensive laser equipment, damaged the PI substrate resulting in (ii) a decrease in bending and folding life, and (iii) a compromise in optical transparency due to the increased roughness of the PI substrate [1]. This research aims to overcome such longstanding shortcomings of LLO processes. Alternatively, this study proposes a swift and in-line coating of a mechanical debonding layer sandwiched between the carrier glass and PI substrate. A novel process was developed to coat a 2D material-based debonding layer between the PI substrate and the carrier glass even under high coating speed. Since the debonding layer forms only weak van der Waals bonding to both the carrier glass and PI, leading to a low debonding force of 1.5 – 2.0 gf/in. This demonstrates an alternative for delamination process that can minimize damage on the flexible displays.

2 Experiment

Aqueous suspension of the raw material (an oxide-based mineral) is dispersed with 10 g/L concentration. The dispersion is stirred under 100 RPM, 80 °C condition for 5 days. Unexfoliated, and thick portion of the raw material is separated through centrifugation, where only the supernatant is processed further. The supernatant containing the exfoliated 2D material flakes is purified through the Bayer process. The supernatant is diluted into 2 g/L concentration. 0.14 g of NaOH is added to the 70 mL of the dispersion, and is placed in the autoclave set at 175 °C for 12 hrs. The unreacted residual NaOH is excluded by series of centrifugation processes. Lastly, the purified dispersion of the 2D material is treated by ultrasonication for 1 hr, for further exfoliation down to monolayered flakes.

Coating the aqueous dispersion of the 2D material flakes consists of mass production-compatible in-line processes only: (i) carrier glass oxidation and cleaning by ambient plasma, (ii) spraying and fully covering the aqueous dispersion on the carrier glass, then (iii) coating of the 2D material-based debonding layer through high-speed drying by air knife. After evaporating residual water in debonding layer under hot air, PI varnish is applied to a uniform thickness on debonding layer and then thermally cured. Measurements of the debonding force was conducted under 90° peel-off testing configuration.

3 Results and Discussion

Since interlayer bonding of the 2D material is relatively weak van der Waals bonding, it can readily be exfoliated. For example, graphene can be produced by mechanical exfoliation of graphite using a scotch tape technique [2]. This offers a key idea to the mechanical debonding as well, in that the same weak van der Waals force can play a role if the 2D material functions as debonding layer.

To replace the existing LLO with the proposed mechanical debonding by 2D material-based debonding layer, (i) a surface coating of 100 % needs to be provided so that the debonding layer can completely block between the carrier glass and the PI substrate. This ensures no direct and strong bonding between PI substrate and the carrier glass can occur. (ii) Also, mechanical debonding keeps merit only if debonding force less than 5 gf/in is achieved, which corresponds to typical peel-off strength of the encapsulation film protecting the device. (iii) The debonding layer must stay intact during the low temperature polycrystalline silicon (LTPS) process at 480 °C, requiring thermal stability to avoid bubble generation underneath the PI substrate. (iv) Lastly, atomically flat debonding layer is preferred to prevent light scattering after the PI is cured, which can be accomplished though exfoliation of the 2D material down to monolayered flakes.

A mineral-based 2D material was selected due to its inexpensive price and already established simple exfoliation process through ultrasonication down to single-layered flakes [3–5]. That material merely shows 3.48 wt% of mass loss up to 600 °C, indicating that this material can circumvent the gas bubble formation between the PI and the carrier glass during the LTPS process. The 3.48 wt% of the mass loss occurs at 100 °C – 150 °C temperature range, suggesting this corresponds to evaporation of the adsorbed water.

The most important process in determining a coating coverage is the 3rd process, air knife for high-speed drying. The surface of the carrier glass is negatively charged, after it was oxidized during the ambient plasma process. The exfoliated 2D material flakes are also negatively charged, indicating 100 % of coating coverage is not possible under nearly equilibrium processes, such as natural convection drying. This air knife process applied in this study is a high-speed drying that is completely out of equilibrium. In other words, when coating was performed through this non-equilibrium process, the electrostatic repulsive force between the 2D material and the carrier glass surface can be overcome by van der Waals attraction. It is consistent with the report that the same charged 2D material flakes can be stacked despite the electrostatic repulsion, if dispersing solvent is rapidly removed[6,7].

It is demonstrated that a low debonding force of 2.10 gf/in can be achieved even by using a high-speed air knife coating process, which can be expanded to a large area production later (**Fig. 1b**). **Fig. 1** illustrates the debonding force as a function of scan speed and air knife pressure. The minimum debonding force is obtained when both the scan speed and the air knife pressure are the lowest. As productivity favors high scan speed, it is necessary to verify whether the debonding force can be kept sufficiently low in this case as well. When the scan speed increases, homogeneous evaporation cannot be induced at the low air knife pressure condition, resulting in non-uniform coating. The optimal debonding layer has 100 % of coating coverage and 2.66 nm thickness.

4 Conclusions

This paper demonstrates a 2D material-based debonding layer, coated from an aqueous dispersion through the mass production-compatible processes can reduce the mechanical debonding force down to ~ 1.50 gf/in. Combination of mass-production compatible equipment, namely spray and air knife can coat the carrier glass surface into ~100 % surface coverage even under the high scan speed. The reported process here can be incorporated into the existing flexible display production processes. Also, the coating methodology outlined in this paper is expected to set a precedent for a general-purpose aqueous chemical-based high-speed and large-area coating technique in the future.

References

[1] J. Bian, F. Chen, B. Yang, J. Hu, N. Sun, D. Ye, Y. Duan, Z. Yin, and Y. Huang, *Laser-Induced Interfacial Spallation for Controllable and Versatile Delamination of Flexible Electronics*, ACS Appl Mater Interfaces **12**, 54230 (2020).

[2] P. Budania, P. T. Baine, J. H. Montgomery, D. W. McNeill, S. J. N. Mitchell, M. Modreanu, and P. K. Hurley, *Comparison between Scotch Tape and Gel-Assisted Mechanical Exfoliation Techniques for Preparation of 2D Transition Metal Dichalcogenide Flakes*, Micro Nano Lett **12**, 970 (2017).

[3] A. v. Tyurnina, I. Tzanakis, J. Morton, J. Mi, K. Porfyrakis, B. M. Maciejewska, N. Grobert, and D. G. Eskin, *Ultrasonic Exfoliation of Graphene in Water: A Key Parameter Study*, Carbon N Y **168**, 737 (2020).

[4] W. J. Lee, C. S. Kim, S. Y. Yang, D. Lee, and Y. S. Kim, *Ultrathin Super-Barrier Film via 100 % Surface Coating Coverage of Self-Assembled Graphene Oxide Sheets*, Chemical Engineering Journal **440**, 135913 (2022).

[5] W. J. Lee, C. S. Kim, S. Y. Yang, D. Lee, and Y. S. Kim, *Spontaneous Exfoliation of Large-Sized Graphene Oxide with Low Defect Concentration by Simple Wet Chemistry*, Carbon N Y **182**, 214 (2021).

[6] J. J. Shao, K. Raidongia, A. R. Koltonow, and J. Huang, *Self-Assembled Two-Dimensional Nanofluidic Proton Channels with High Thermal Stability*, Nature Communications 2015 6:1 **6**, 1 (2015).

[7] K. Raidongia and J. Huang, *Nanofluidic Ion Transport through Reconstructed Layered Materials*, J Am Chem Soc **134**, 16528 (2012).

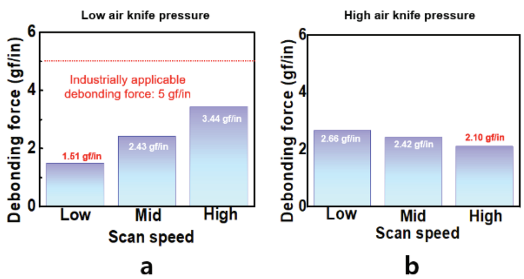

Fig. 1 Minimization of mechanical debonding force by the optimal coating of the 2D material-based debonding layer under **a** low air knife pressure, and **b** high air

knife pressure conditions.