Continuous manufacturing of blazed angle-tunable prismatic micro/nanopatterns by axis-tilted nanoinscribing

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ABSTRACT

The blazed micro- and nanopatterns have recently been of increasing interest as functional diffraction gratings possessing low polarization dependent loss, and high rotational efficiency. Fabrication of the blazed grating patterns based on conventional nanopatterning protocols such as photolithography, nanoimprint lithography, or e-beam lithography, however, often demands a lot of time and cost. In that regard, we develop Z-axis-tilted Dynamic Nano-Inscribing (Z-DNI) technique which can continuously create the blazed micro- and nanopatterns by sliding a rigid tool edge mounted at a tilted angle over diverse flexible polymer substrates (*e.g.*, polycarbonate, polyimide, PET, *etc.*). Z-DNI can readily tune the blazed angle, grating period, and processible area by controlling the tilting axis, shape, and stroke distance of a grating tool. We also investigate that the substrate-contacting force and local temperature of a tool as well as its inscribing speed influence the depth and sharpness of the blazed patterns. Through a systematic study on those important parameters, we can determine the optical processing conditions for the blazed patterns of desired blazed angles and periods on desired substrate materials. The low-cost, highly reproducible fabrication of blazed micro- and nanopatterns with specific designs can be implemented by Z-DNI, which will lead to practical flexible electronic, photonic, and sensing device developments.

Keywords: Nanopatterning, Axis-tilted nanoinscribing, Slanted pattern, Blazed pattern, Flexible substrate, Polymer deformation

1. INTRODUCTIONS

The slanted micro- and nanopatterns have not only high diffraction efficiency, but also the advantages of improving the sensitivity, resolution, and measurement range of grating measurement systems. So, they are widely used in several mobile optical applications such as backlights and virtual displays.[1] In order to form such a blazed pattern, fabrication of the blazed grating patterns based on conventional nanopatterning protocols such as photolithography, nanoimprint lithography, and e-beam lithography have been used and studied. However, it not only demands a lot of time and cost, but also induces defects in the pattern. In addition, the above processes involve additional time and cost to change the inclined angle, period, and shape of the pattern.

In this study, as a method that can overcome the limitations of existing processes, we develop Z-DNI process that can continuously and rapidly create large-area grating patterns of various shapes through only one-step. Advancing from (or “Applied in”) the DNI process that can create rectangular nanograting patterns[2], the Z-DNI process can simply customize slanted and blazed patterns with various shapes, periods, and transmittances by rotating the mold which is contacting the substrate at a specific angle in the Z-axis direction. In addition, this process can be simplified because the pattern is directly formed on the flexible substrate based on the plastic deformation characteristics. In the Z-DNI process, since patterns are formed through plastic deformation of polymer, pressing force, mold temperature and inscribing speed act as major process parameters. Therefore, we analyze the mechanisms of each process variable that depend on the rotation angle to create patterns of various shapes highly reproducible with high quality as needed and suggest optimal pattern formation conditions at a specific angle. Furthermore, we not only present the versatility of the Z-DNI process by forming slanted patterns on substrates of various materials, but also present the excellent potential of this process by showing the possibility of applying a diffractive lens as an application.

2. RESULTS AND DISCUSSION

2.1 Process principle

Z-DNI can produce micro- and nanopatterns on a polymer substrate at high speed and continuously based on the principle of direct mechanical processing. The process sequence is as follows. The cleaved grating mold of rectangular patterns is attached to the mold arm of the Z-DNI process system. The flexible substrate is placed on the transfer stage to which the rubber pad is attached, and the angle between the mold arm and the substrate is adjusted to the specific angle by rotating the rotate stage. And then, it is possible to form slanted patterns in one-step process by pressing the substrate with a specific force with the edge of the mold and moving the transfer stage at a constant speed. If necessary, the mold arm is heated to increase the temperature of the mold to increase the formability of the flexible substrate. The Z-DNI process system and the inscribing principle can be seen in the Fig. 1(a) schematic. Since the Z-DNI process forms patterns based on the plastic deformation characteristics of the film by the force and temperature of the mold pressing the substrate, micro-nano scale grating patterns can be easily formed without burrs. Figs. 1(b-e) show optic images of patterned film and SEM images in which patterns were formed at various rotation angles through this process. It can be seen that the shape and period of the patterns change according to the rotation angle θ. Here, the period decreases by cos θ according to the rotation angle.

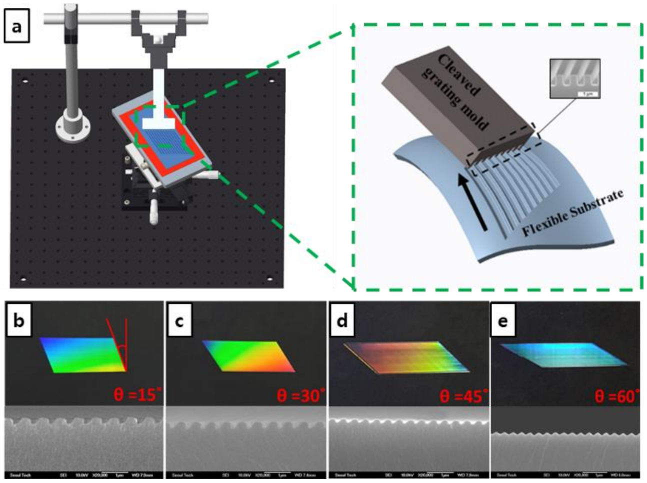

Figure 1. (a) The schematics of Z-DNI process system and inscribing principle. Film image and SEM image at a rotation angle of (b)15 (c)30 (d)45 (e) 60 degrees.

2.2 Process variables Analysis

In this process, since patterns are formed through plastic deformation of polymer, it is important to control the process variables that affect the deformation of the polymer in order to form patterns of various shapes according to rotation angle with high reproducibility. Therefore, we analyzed the pattern formation results for major process variables such as pressing force, mold temperature and inscribing speed, which have a dominant influence on plastic deformation.

Physical deformation by pressing force and thermal deformation by mold temperature are major factors that determine the pattern shape and depth. When the mold is rotated, as shown in fig. 2(a), the pattern depth decreases as the pressing force increases. This force dependence can be explained by a side opening appearing with rotation as shown in fig. 2(b), and the flow of a certain amount of polymer in this direction during the patterning process. As a large amount of polymer that exceeds the mold opening, which determines the shape of the pattern, is deformed by a large force, the flow of polymer to the side opening increases, resulting in an increase in pattern width and decrease in depth. In addition, at a high mold temperature such as 150°C, which is the Tg(glass transition temperature) of the PC film used as a substrate, the same phenomenon occurred as when the pressing force is large even if it is small, resulting in a lower depth of the pattern. This is because the viscosity of the polymer decreases with high temperature and the fluidity increase. The effect of high temperature on the pattern formation result is greater as the rotation angle increases. As shown in fig. 2(c), in 60 degrees, not only the lowest depth pattern is formed at 150°C, but also the second lowest depth at 110°C, which showed the maximum depth at a rotation angle of 30 degrees.

The pattern formation result according to the temperature can vary depending on the inscribing speed. Fig. 2(d) shows the pattern depth for each temperature according to the inscribing speed at a rotation angle of 30 degrees. At 110°C, the pattern with the highest depth is formed at the basic process speed of 1mm/s. With a constant viscous flow at the temperature and force(2N), if the inscribing speed is increased, the polymer does not deform enough to fill the mold opening. Conversely, if the speed is decreased, the flow to the side opening increases due to excessive deformation and the depth decreases. That is, the results are like when the force is very weak or large. At 150°C, the pattern with the highest depth is formed at a high speed of 5mm/s because the polymer flow is increased by the high temperature. At speeds above or below 5mm/s, the depth decreases with the same phenomenon as at 110°C. On the contrary, at the low temperature of RT(Room Temperature), the highest depth is obtained by securing sufficient deformation time at a slow speed of 0.1mm/s.

Through this parametric analysis of major process variables, we discovered the optimal process variables that can form the highest depth pattern for each rotation angle with high reproducibility. In this process, an optimal pattern was formed at 110°C at a rotation angle of 30 degrees, and RT at a rotation angle of 60 degrees. The process speed is 1mm/s and pressing force is 2N, which is the same at both angles.

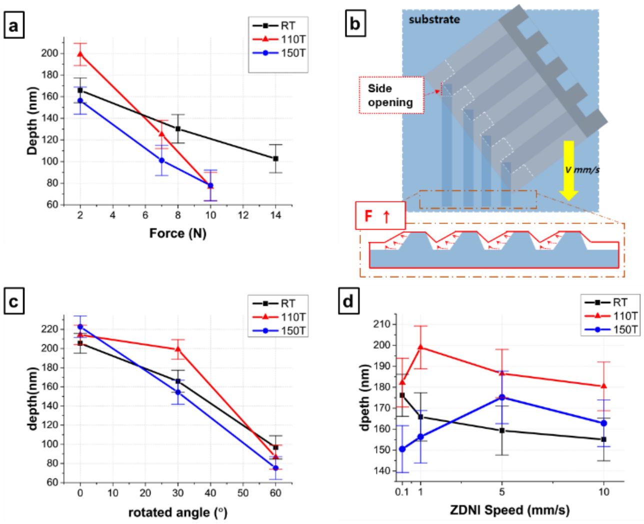

Figure 2 (a) The graphs of patterns depth according to the pressing force at rotation angle of 30 degrees. (b) The schematic of patterning process at rotation angle of 30 degrees and large pressing force. The

graphs of patterns depth according to (c) the rotation angle and (d) the inscribing speed at angle of 30 degrees for each temperature.

2.3 Process application

The Z-DNI process can be applied to a variety of substrates as well as PC film substrates, so a pattern of a desired shape can be manufactured by selecting a substrate according to customization, thereby expanding its utility. Figs. 3(a-d) show the SEM images and optic images of the various film substrates through the Z-DNI process with a rotation angle of 30 degrees. Figs. 3(a-d) is PC, PET, PFA, PI film in order, and pressing force is a relatively small force of 2-5N. We set the temperature considering the physical properties (*e.g.,* glass transition temperature, melting temperature, *etc.*) of each film and the carry out the Z-DNI process. The slanted patterns are formed on all four films.

In addition, we present the possibility of application as a flexible diffractive lens by rotating the substrate under pressure with a mold to form slanted and blazed patterns of different shapes on the film substrate in a circular shape. Fig. 3(e) shows the optic image of a PC film in which patterns were formed in a circle at different angles using the same mold. We formed patterns with different shapes and periods by inscribing at rotation angles 0, 30 and 60 degrees from the outside in the center of the circle. Since these patterns with different inclinations, even though a flat film, light is refracted at different angles and focused. As such, it is possible to form patterns in a circular shape as well as a straight through this Z-DNI system, so it is expected to be widely used in various fields.

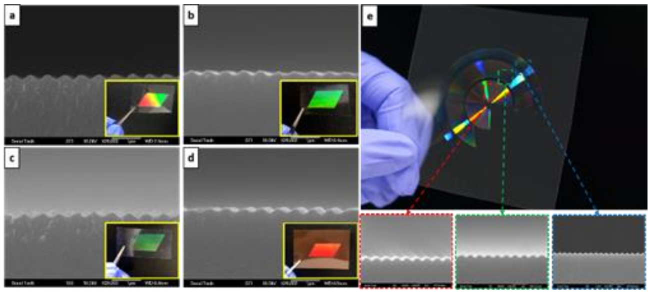

Figure 3 SEM images and optic images of slanted patterns on (a)PC (b) PET (c) PFA and (d) PI film. (e) Optic images formed in circular shape at different angles and SEM images for each location**.**

3. CONCLUSION

Through the Z-DNI process, we suggest conditions for reproducible high-quality patterns of various shapes by analyzing the combination of the three variables and the adjustment of the rotation angle of the mold. By establishing the optimal conditions for continuously producing large-area patterns of various shapes through parametric analysis, patterns of desired shapes can be easily and reproducibly produced. In addition, the excellent applicability of this process was confirmed by forming slanted patterns on various film substrates and forming patterns in a circular shape. Therefore, the advantages of Z-DNI process such as low cost, high speed, high productivity, and compact system are expected to be applied and utilized in various fields like flexible electronic, photonic, and sensing device developments.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grants (No. 2015R1A5A1037668 (MSIT), No. 2020R1F1A1073760 (MSIT), and No. 2019R1A6A1A03032119 (Ministry of Education)) and the Commercialization Promotion Agency for R&D Outcomes (COMPA) grant (No. 2019K000591 (MSIT)), funded by the Korean Government.

REFERENCES

[1] Gao, J.; Chen, P.; Wu, L.; Yu, B.; Qian, L., A Review on Fabrication of Blazed Gratings. Journal of Physics D: Applied Physics 2021.

[2] Oh, D. K.; Lee, S.; Lee, S. H.; Lee, W.; Yeon, G.; Lee, N.; Han, K. S.; Jung, S.; Kim, D. H.; Lee, D. Y.; Park, H. J.; Ok, J. G., Tailored Nanopatterning by Controlled Continuous Nanoinscribing with Tunable Shape, Depth, and Dimension. Acs Nano 2019, 13 (10), 11194-11202.