Fabrication of advanced thin film for high performance display by nanoimprinting process via gallium oxide solution doped tin

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Abstract

Line pattern replication process through nanoimprint lithography (NIL) method has been used in numerous research fields. NIL technology is not yet utilized for displays industry, and we propose an alignment layer of the sol-gel process using NIL. One-dimensionally nanopatterned by polydimethylsiloxane sheets cause surface changes in hybrid SnGaO thin films mixed in a 3:7 ratio, which aligns the liquid crystals (LCs) uniformly in the line pattern direction. These surface changes are confirmed through atomic force microscopy data analysis, and changes in surface shapes for different the curing temperatures in the furnace are analyzed. X-ray photoelectron spectroscopy shows that the chemical composition of the thin films changes according to curing temperatures, and the intensities of SnO and GaO increase exponentially at 200°C compared to those at 50 °C. Through this, the van der Waals force increases between surface molecules, in the anisotropic direction to help align the LCs. Furthermore, we performed polarized optical microscopy and pre-tilt angle analysis confirm that the LCs are energized uniformly. Finally, the performance of an actual display device transmittance and electro-optical properties; the transmittance of SnGaO is 4.51p% higher than that of the currently commercialized PI-rubbing, and the voltage-transmittance curve is a perfect graph.

Keywords: nanoimprint lithography, gallium oxide, tin oxide, sol gel process, liquid crystal display
1. Introduction

Owing to the rapid development of semiconductor devices in recent years, the demand for advanced display devices has increased significantly. Among the various display types, liquid crystal displays (LCDs) are being applied to various electronic devices, such as TVs, smart phones, head up displays, and augmented realities/virtual realities using the structural arrangement of thin-film transistor (TFT) devices. \[1,2\] Therefore, many studies are being conducted to improve the functions of LCDs in which liquid crystals (LCs) are the key materials. LCs are mysterious substances that exhibit anisotropy in their refractive and dielectric constant indices and have elastic as well as collective properties as they exist in an intermediate state between liquid and solid. \[3–5\] One of the important factors controlling LCs is their alignment layer. There are different methods for aligning LCs via different treatments of the alignment layer. For example, rubbing, \[6,7\] evaporation, \[8\] plasma-treatment, \[9\] sputtering, \[10\] photo-alignment, \[11\] ultraviolet (UV) irradiation, \[12\] and ion-beam irradiation. \[13, 14\] Existing rubbing treatment processes are among the most effective methods to align LC molecules during LCD fabrication. \[15\] The currently used rubbing method is widely applied in industry because of its simple process, high reliability, and low cost. \[16\] However, physical contact with the alignment layer has been reported as a serious problem. The rubbing process induces accumulation of static electricity and generation of fine dust, which destroys the TFT and lowers the quality of the LCD. \[17\] This can also introduce debris, resulting in film damage from scratching at the boundary surfaces and low thermal budget owing to the use of polyimide (PI) films, all of which may cause fatal shocks to the TFTs used in the LCD panels and subsequent breakdown of the electronic devices. Hence, scratch and oxidation prevention are suggested using the sol-gel process that is often applied in anti-reflection, light/infrared absorption, conductivity, and weather resistance processes. The sol-gel process does not require expensive equipment, \[18, 19\] unlike conventional deposition methods such as atomic layer deposition (ALD) \[20\] and electron beam (e-beam) deposition. \[21\] In addition, alignment films generated via sol-gel processing do not need to be treated by an LC alignment process \[22\] (e.g., rubbing, UV alignment, or IB irradiation). We also present a more efficient LC alignment method using nanoimprint lithography (NIL). \[10,23–25\] Here, we use one-dimensional nanostructure patterns on silicon wafers etched by laser interference lithography (LIL). \[26\] These patterns are replicated on polydimethylsiloxane (PDMS) sheets for application as a master stamp. The master stamp is used to move the nanostructure of the orientation layer continuously. This facile nanoimprinting method is applicable to both organic and inorganic films. Compared to conventional organic materials, inorganic materials have the advantages of excellent heat resistance, high transparency, and clear electrical properties. \[27–29\] Therefore, they are applied to various electrical devices and have differentiated characteristics. Based on these advantages, many inorganic materials are still selected as alignment layers today. ZnSnO has been proven with various TFTs of SnO-based AMOS (ZrZnSnO, BaZnSnO, MgZnSnO). \[30,31\] Most of these materials contain zinc and use the weak Zn-O bonding. ZnSnO is mostly manufactured by the vacuum process, which requires high cost and a complicated process. Therefore, we use gallium in the thin film to replace Zn. Ga has higher oxygen affinity than Zn as well as higher formation energy for oxygen vacancies, so it can be used together with Sn as a carrier inhibitor. \[32\] Gallium oxide is a binary metal oxide of group III; \[33,34\] it exhibits electrical properties at room temperatures but exhibits semiconducting properties at high temperatures because of oxygen deficit. GaO is an efficient material for power and high-voltage electronic devices. The band-gap of Ga2O3 is much larger than that of GaN, and it can be used as an efficient host material for rare-earth and transition-metal-based phosphors.
2. Experiment

2.1 Preparing SnGaO Solution via Sol-Gel Method

Figure 1a shows SnGaO thin films prepared by the solution process on indium-tin-oxide (ITO)-coated glass substrates (Samsung corning 1737: standard 32×22×1.1 mm³, sheet resistance 10Ω·h⁻¹). Prior to deposition, the ITO glass substrates were sonicated in a trichloroethylene (TEC), acetone, methanol, and deionized water solution for 10 min and dried with N₂ gas. Thereafter, tin(II)-chloride (SnCl₂) and gallium(III)-nitrate hydrate (Ga(NO₃)₃·xH₂O) were dissolved in 0.1 mol L⁻¹ of 2-methoxyethanol (2ME), respectively. SnCl₂ was stirred at 75 °C for 2 h and Ga(NO₃)₃·xH₂O was stirred at 80°C for 1 h using a magnetic stirrer to yield a homogeneous and stable colloid solution. These solutions were aged at room temperature for stabilization. Then, we mixed SnO:GaO in a 3:7 ratio accurately. As gallium and tin are oxidized, they combine with each other; the schematic representations of ionic...
bonding in an ideal SnGaO system is illustrated in Figure 1b.

Figure 1. Schematic of solution manufacturing process for nanopatterned thin film. (a) Hybrid sol-gel process; SnGaO solution is prepared by mixing 0.1 mol of SnO and 0.1 mol of GaO dissolved in 2ME in a 3:7 ratio. (b) Oxidation bond model of Sn and Ga molecules. (c) Manufacture of polydimethylsiloxane (PDMS) sheets with nano line pattern for nanoimprint lithography (NIL) process.
2.2 Manufacturing of One-Dimensional Nanopattern by NIL

Figure 1c shows the schematic illustrates for manufacturing the PDMS mold by mixing a silicone elastomer base and a curing agent (SYLGARD 184, Dowhitech Corp.) in a 10:1 ratio and pouring over Si wafer surface with a periodicity of 750 nm, width of 450 nm, spacing of 300 nm, and height of 30 nm. Then, a vacuum system was constructed to remove the air bubbles over a duration of 1 h and cured at 80 °C for 1 h. After curing, the stiff PDMS mold was removed and used for imprinting nanostructures on the SnGaO thin-film surfaces.

2.3 Replication of Nanopattern on SnGaO Thin Films via Furnace

To prepare the SnGaO thin films, the solution was spin coated the glass substrates at 3000 rpm for 30 s. Furthermore, the previously manufactured PDMS mold was attached to the SnGaO films, and the samples were cured for 1 h at 50, 100, 150, and 200 °C in a furnace. The peeled-off film surfaces then retain the nanopatterned structures. The embossing process transferred the aligned pattern on the PDMS mold onto the SnGaO layer. Underneath, the SnGaO liquid solution fills the indentations in the PDMS pattern by capillary pressure, which is then solidified by heating.

2.4 Fabrication of Liquid Crystal Cells based on Replicated Nanopattern SnGaO Thin Films

SnGaO films were assembled above and below in an antiparallel orientation with a uniform cell gap of 60 μm and injected with negative LCs (ZSM-7228XX, Δn = 0.109, nₑ = 1.596, nₒ = 1.487, Δε = -3.0, JNC Co., Ltd) using a syringe (KOVA) in a direction parallel to the 1-D nanopattern via capillary force.

2.5 Measurement of Surface and Electro-Optical (EO) Properties

To characterize the LC orientations, polarized optical microscopy (POM; BXP 51, Olympus) measurements and pretilt angle calculations via the crystal rotation method (TBA 107; Autronic) were used to investigate the LC alignment status. To estimate the EO performance, twisted nematic cells were fabricated with the nanopatterned SnGaO films. The two SnGaO films were assembled to intersect with each other through a uniform cell gap of 5 μm, and the negative LCs were injected. The voltage–transmittance (V-T) curves were then obtained using an LCD evaluation system (LCMS-200; Sesim) as the applied voltage was varied from 0 to 5 V. The chemical compositions of the SnGaO films were investigated by X-ray photoelectron spectroscopy (XPS; ES-CALAB 220i-XL, VG Scientific). The XPS measurement principle uses a monochromatic X-ray source, where the X-rays collide with the parallel crystal planes at an angle θ and are reflected at the same angle. Furthermore, the Bragg equation (nλ = 2d sinθ) and X-ray monochromators, are used in combination with K-alpha radiation. Based on these principles, we confirm the binding energies of the Sn, Ga, C, and O atoms of the main chemical components.
3. Results and Discussion

An AFM image of the SnGaO film is shown in Figure 2, which depicts the three-dimensional shape and cross section of the PDMS template surface before imprinting and after pattern transfer. It can be seen that the PDMS template is imprinted as a thin film in a liquid state containing a solution filling the depressions of the nanopattern. For the non-engraved PDMS template, the morphology of a flat thin film can be seen. Figure 2 shows the 3-D morphology of the alignment pattern transferred via the embossing process onto the SnGaO layers at temperatures 50 °C, 100 °C, 150 °C, and 200 °C. As seen from the 3-D images, the shapes of the line patterns are clearly visible. When the annealing temperature is 50 °C as in Figure 2a, clear line patterns are visible, but they are faint and have low height. Moreover, in the 100 °C process, the line patterns were not perfectly replicated, as seen in Figure 2b. However, as the annealing temperature is gradually increased, the height increases and most of the crystals are obtained upward at 150 and 200 °C, as seen in Figure 2 c and d. At a glance, it appears that there are no line patterns, but the 2-D image in Figure 2e, shows that the lines are clearly transferred. The narrow peaks seen at 150°C and 200°C are the growths of the combined SnO and GaO crystals, and not defects. As the SnGaO crystals are successfully bonded and grown, it is seen that the van der Waals interaction acts strongly on the thin films, as expressed in Equation (1).

\[
E_{vdw} = \frac{A_{ij}}{r_{ij}^6} - \frac{B_{ij}}{r_{ij}^{12}}
\]

The patterns obtained on the base films were used as the alignment layers for the LC cells.

Figure 2. Atomic force microscopy (AFM) 3-D images topographies of the tin-gallium oxide thin films via nanoimprint
lithography process and surface shape changes based on curing temperatures using a furnace; (a) 50 °C, (b) 100 °C, (c) 150 °C, and (d) 200 °C. Typical size of the 3-D image was analyzed as 5×5 µm, with a height of unit of 60 nm. (e) 2-D image of the 200 °C process showing the most surface changes due to chemical molecular bonding; at first glance, it appears that the pattern has not been replicated; however, the pattern is clearly copied upon closer observation.

As seen in Figure 3 a and b, the amplitudes of the line pattern profiles are very low for the 50 °C and 100 °C processes; this means that the template of the PDMS was completely replicated, but the SnO and GaO crystals did not react adequately at low temperatures. On the other hand, as the temperature increased gradually, the amplitude increased; at 200 °C, the amplitude was about twice that at 50 °C. As mentioned above, the increase in amplitude is due to the binding and growth of the SnGaO molecules, which have strong van der Waals interactions. Based on these observations, linear nanopatterns can be used to direct the alignments of the LC molecules. It should be noted that the PDMS pattern had an average line pattern periodicity of 750 nm, width of 450 nm, spacing of 300 nm, and height of 30 nm. The pattern of the SnGaO solutions had an average line pattern periodicity of 703 nm, width of 351 nm, spacing of 234 nm, and height of 48 nm after annealing at 200 °C, as shown in Figure 3d. After imprinting the patterns, the inverse replicas of the PDMS templates with similar width, spacings, and line periods were obtained.
The XPS survey scans were recorded in the range of 480–500 eV for Sn3d, 1114–1124 eV for Ga2p, 18–28 eV for O 1s, and 281–286 eV for C 1s of the SnGaO films cured at 50 and 200 °C as shown in Figure 4, for increasing curing temperatures. First, the SnO spectra in Figure 4a were separated into Sn3d5 and Sn3d2/3 by spin-orbit splitting. The peak binding energies of Sn3d5 and Sn3d2/3 are centered at 486.15 eV and 494.78 eV at 50 °C, respectively. Otherwise, the peak binding energies of Sn3d5 and Sn3d2/3 are centered at 486.14 eV and 494.64 eV at 50 °C, respectively. Further, the GaO spectra in Figure 4b and c were separated into Ga2p3/2, Ga2p1/2, Ga3d3/2, and Ga5d by spin-orbit splitting. The binding energies of Ga2p3/2 and Ga2p1/2 for the SnGaO films cured at 50 °C are centered at 117.44 eV and 1121.33 eV, and the binding energies of the Ga2p3/2 and Ga2p1/2 for the SnGaO films cured at 200 °C are centered at 1117.41 eV and 1121.89 eV, respectively. The binding energies of Ga3d3/2 and Ga5d for the SnGaO films cured at 50 °C are centered at 19.89 eV and 24.97, and the binding energies of Ga3d3/2 and Ga5d for SnGaO films cured at 200 °C are centered at 19.79 eV and 26.04 eV, respectively. Similarly, the O 1s and C 1s spectra in Figure 4d and e were observed. The binding energies of O1, O2, Ochem, and C 1s for SnGaO films cured at 50 °C are centered at 531.31 eV, 529.93 eV, 532.24 eV, and 283.67 eV, and those for the SnGaO films cured at 200 °C are centered at 531.28 eV, 529.73 eV, 532.19 eV, and 283.82 eV, respectively. As seen in Figure 4, the intensity changes considerably according to the curing temperature. First, in the case of the SnO molecules, the intensity of the Sn3d5 (red spectrum) element samples cured at 200 °C increased 10.99 times compared with that cured at 50 °C. From the elements of Sn3d2/3 (blue spectrum), the intensity of the sample cured at 200 °C increased by 10.74 times compared with that cured at 50 °C; these observations can also be confirmed by the numerical values of the atomic percentages of Sn3d5 in Table 1. Atomic percentages of the samples cured at 50 °C was 0.37%, but cured at 200 °C was 3.97%, which is an increase of about 3.6p%, or 10 times. Furthermore, there are large change in the case of the GaO molecules. In the case of
the Ga2p\textsubscript{3/2} element sample, the intensity at 200 °C increased 7.37 times compared to that at 50 °C, and for Ga2p\textsubscript{1/2} element sample, the intensity at 200 °C increased 101.94 times compared to that at 50 °C. Then, the intensity of the Ga3d\textsubscript{3/2} element sample at 200 °C increased 8.04 times compared to that at 50 °C, and the element of the Ga5d sample at 200 °C increased by 3.91 times. This is also confirmed from the atomic percentage value of Ga2p in Table 1. The Ga2p\textsubscript{3} atomic percent at 50 °C in Table 1a is 0.36% and that at 200 °C in Table 1b is 2.14%, which is an increase of 1.78p%. However, as shown in Figure 4d, the spectrum of O 1s presents an opposite trend. The O1 element has a slightly reduced shape, but the oxygen vacancy does not change significantly. Therefore, it can be confirmed that detachment of the oxygen atoms does not form oxygen vacancies, and SnO and GaO show van der Waals interactions during crystal growth crystals. In addition, it is again confirmed that the intensity of carbon atoms does not change significantly.

**Figure 4.** Chemical composition spectra variations of SnGaO through X-ray photoelectron spectroscopy analysis. The X-ray source used monochromate Al Kα with an ultimate energy resolution of 0.50 eV full-width at half maximum (FWHM) of the Ag3d intensity curve and ion source energy range of 100 V to 3 keV. (a) Sn3d\textsubscript{5} and Sn3d\textsubscript{2/3}, (b) Ga2p\textsubscript{3/2} and Ga2p\textsubscript{1/2}, (c) Ga3d and Ga5d, (d) O1-, O2-, and O\textsubscript{chem}, and (e) C1s.
Table 1. Binding energy, full width half maximum, and atomic percent values of Sn3d5, Ga2p3, O1s, and C1s. (a) is 50 °C. (b) is 200 °C

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<th>Peak Binding Energy (eV)</th>
<th>FWHM (eV)</th>
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<td>Sn3d5</td>
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(a)

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<th>Peak Binding Energy (eV)</th>
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<tr>
<td>Sn3d5</td>
<td>486.14</td>
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(b)

Transparency (V–730 UV/VIS Spectrophotometer, JASCO) is an essential property in applications to display devices. The basis of measurements with the spectrophotometer is that when an atom or molecule receives external light energy, the electrons in the atom or molecular orbitals absorb the light and undergo transitions. At this time, only light with energy equal to the energy required for transition is absorbed. Light energy is proportional to wavelength as shown in the equation below, so visible light is absorbed at a different wavelength from UV light according to the energy required for transition. Here, E is the energy of light, h is Planck’s constant, and v is the frequency in Equation (2).

\[ E = h \times vE \]  

(2)

\[ A = -\log T = \log \left( \frac{P_0}{P} \right) = abc = \epsilon bc \]

(3)

Moreover, the Beer–Lambert law in Equation (3) is an expression of the linear relationship between the absorption concentrations of the electromagnetic waves and absorption values, where \( P \) and \( P_0 \) are the radiation intensities of light energy per square centimeter area of the detector per second, \( A \) is the absorbance, \( T \) is the transmittance, \( b \) is the passage of radiation, \( a \) is the absorption coefficient, and \( \epsilon \) is molar extinction coefficient.

As shown in Figure 5, in the visible region of 380–780 nm, the average optical transmittances of the single-deposited nanopatterned layer are 84.24%, 85.93%, 85.28%, 87.04%, and 87.74% for 50 °C, 100 °C, 150 °C, 200 °C without stamping, and 200 °C, respectively. For comparison, a commercial PI-coated glass has an average transmittance of 83.23%. As expected, the optical transparency properties of the nanopatterned layer generally
increase as photons of visible light are captured by the periodic nanostructure according to waveguide mode theory. Furthermore, the transmittance for SnGaO cured at 200 °C with template replication is 4.51p% higher compared to that of commercial PI-coated glass.

Figure 5. UV-vis transmittances of the SnGaO thin films according to curing temperatures. The measured wavelength range is 250–900 nm, and the visible range is 380–780 nm.

Figure 6 depicts the POM images of the fabricated LC cells and expected LC alignment on the nanopatterning-imprinted SnGaO layer. The LC cells fabricated at 200 °C by nanopattern transfer onto the SnGaO layers show uniformly aligned LC states, as in Figure 6d. Under the condition of a well-transferred nanopattern, the LCs are aligned in a single direction parallel to the surface pattern, which acts as a guide. [35] Around the surface, the LC molecules are localized in nanopatterned intersperse, and owing to the collective behavior of the LCs, these anisotropic molecules migrate to the bulk and are arranged along one direction. Figure 6 illustrates the principle of alignment of the LCs by anisotropy. [36] Furthermore, the action of van der Waals forces between the LCs and SnGaO thin film helps determine the alignment direction according to the anisotropy of the LCs. As mentioned earlier, negative LCs were used during fabrication, and the direction of the long axis (n_o) is along the direction perpendicular to the thin film. This corresponds to SnGaO films formed at 200 °C curing conditions. On the other hand, in a randomly dispersed state, there is no guide to the LCs, so they spread chaotically over the surface. Hence, we confirmed the existence of homogeneously aligned LCs on the nanopatterned SnGaO films. The principle of POM is illustrated in Figure 6e. When the nanopattern is parallel to one axis of the cross polarizer,
light propagates in a straight line through the parallel LC molecules and is blocked by the cross polarizer on the upper substrate. Evenly aligning the LCs and rotating the cell by 45° maximizes light transmission through the crossed polarizers. Therefore, it is confirmed that LC cell rotation under the crossed polarizer maintains uniform alignment. The orientation of the nanopattern was between the polarizers intersecting at angles of 45° with the orientations of the polarizers. Therefore, we confirmed homogeneously aligned LCs on the nanopatterns.

**Figure 6.** Polarized optical microscopy (POM) images of one-dimensional nanopatterns on SnGaO thin films via furnaces of liquid crystal (LC) cells with 60 μm gap and negative LCs (Δε = 0.109, nₑ = 1.596, nₒ = 1.487). The letters "A" and "P" represent the analyzer and polarizer axes, respectively, at (a) 50 °C, (b) 100 °C, (c) 150 °C, and (d) 200 °C. (e) Principle of light passing through the polarizer and analyzer according to alignment and non-alignment of the LCs in POM. (f) Schematic of LC arrangement with or without 1D nanopatterns on SnGaO thin films as well as reactions between the alignment layer and LCs.

Furthermore, the LC alignment status could be confirmed through pretilt angles by the crystal rotation method.
Figure 7 shows a graph of experimental blue curve and simulated pretilt angle curve of red. The blue curve was extracted based on well-aligned LCs using birefringence information and coincides with the red curve, indicating that the LC molecules are well align along the same direction and that the pretilt angle was calculated with high confidence. As can be seen from the figure, the most uniform pretilt value is 200 °C in Figure 7d. Ultimately, average of pretilt angle value is 90.1898° at 200 °C, consistent with the previously mentioned POM analysis for LCs of the nano patterned are homogeneously aligned on SnGaO thin films. Likewise, the error rate is indicating the smallest value of 0.001937 % shown in Figure 7e as evidence of having the best alignment at 200 °C.
Figure 7. Measurement of the pretilt angles; transmittance measurements are performed under latitudinal rotation.
using the crystal rotation method on SnGaO thin films at (a) 50 °C, (b) 100 °C, (c) 150 °C, and (d) 200 °C. (e) Comparison of the pretilt angle error rates of the LC cells by curing temperatures.

The EO properties are one of the essential elements of displays because they are responsible for power consumption and reaction speed. Therefore, to confirm the EO potential of the SnGaO thin films with imprinted nanopatterns, an LCD evaluation system (LCMS-200; Sesim Photonics Technology) was used for the measurements. [37, 38] The voltage–transmittance characteristics were poorer than those using the rubbing method, with notable optical bounce effects. The threshold voltage is also an important factor for electronic devices and is measured as 2.13 V, as shown in Figure 8, which also illustrates the changes in the arrangement of the LCs in the vertical alignment (VA) mode. At 0 V, the major axis of the LCs is directed upward, and light is not transmitted. However, when 5 V is applied, the minor axis is directed upward, and light is transmitted. Thus, vertically aligned LCs with negative dielectric anisotropy lie horizontal to the electric field such that light from the bottom can pass through the LC matrix via circular polarization.

![Figure 8](image)

**Figure 8.** Transmittance versus voltage curve of the VA LC cells (cell gap: 6 μm) fabricated using SnGaO thin films at 200 °C in a furnace via NIL method.
4. Conclusion

Nanopatterning is an upcoming technology that enables improving the properties of semiconductor and display devices. We use 1D nanostructure patterns on silicon wafers etched using LIL to duplicate the patterns onto PDMS sheets for application as base stamps. Changing the surface chemical composition by adjusting the surface energy improves the voltage–transmittance characteristics. AFM images showed superior patterned grooves at a curing temperature of 200 °C. Thus, the nanostructure patterns on the films acted as alignment guides for the LC molecules on the surface. In addition, XPS analysis shows that oxygen vacancies and oxygen intensities tend to decrease as the curing temperatures increase to 200 °C; the carbon intensity also increases slightly, indicating more active thermal oxidation. However, the important thing here is that the intensities of SnO and GaO increase significantly. From numerical analysis of the graphs, the intensities of Sn3d5 and Sn3d2/3 elements were observed to increase by more than 10 times at 200 °C, and this was similar to the atomic percentage of Sn3d5 increasing by about 10 times (3.6p% increase). In addition, the intensity of the Ga2p3/2 element increased by about 7 times at 200 °C, and the atomic percentage increased by about 6 times (1.78p%). The growth of these sol-gels actively helped the van der Waals interactions and allowed the LC molecules to be perfectly vertically aligned. Therefore, the chemically modified structures induce nanopattern structures on the surfaces of the SnGaO thin films at high curing temperatures and help the elasticity of the LCs. LC alignments and pretilt angles were induced by the directional peeling effect when using the PDMS molds. Excellent EO properties of the thin films were also confirmed through V-T measurements. Thus, characteristics such as the reaction speed and power consumption were improved; these improvements allow utility of the produced films in industrial production of display electronic and photonic devices. Furthermore, NIL technology is suitable for large-area processes and is applicable to both soft organic and rigid inorganic layer alignment methods. The GaO solution combined with SnO through embossing can be reproduced on a large scale, and various changes can be made by varying the mixing ratios according to consumer demands. Tin-doped gallium thin films are thus proposed here as alternatives to future display device materials.
Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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