Displays 36 (2015) 21–29

Contents lists available at ScienceDirect

Displays

journal homepage: www.elsevier.com/locate/displa

Developing novel liquid crystal technologies for display and photonic applications

Hari M. Atkuri [a], Eunice Sok Ping Leong [b], Jeoungyeon Hwang [c,d], Giovanna Palermo [e], Guangyuan Si [f], Jenny-Marie Wong [d], Liang-Chy Chien [d], Ji Ma [d], Kaichang Zhou [g], Yan Jun Liu [b], Luciano De Sio [c,e,*]

[a] R&D Engineer, Cardinal IG Technology Center, 7201 W Lake St, Minneapolis 55426, MN, USA
[b] Institute of Materials Research and Engineering, Agency for Science, Technology and Research (A*STAR), Singapore 117602, Singapore
[c] Beam Engineering for Advanced Measurements Co., Winter Park, FL 32789, USA
[d] Liquid Crystal Institute, Kent State University, Kent, OH 44240, USA
[e] Department of Physics and Centre of Excellence for the Study of Innovative Functional Materials (CEMIF-CAL), University of Calabria, Arcavacata di Rende 87036, Italy
[f] College of Information Science and Engineering, Northeastern University, Shenyang, Liaoning 110004, China
[g] First Solar Inc., Toledo, OH 43604, USA

ARTICLE INFO

Article history:
Received 19 August 2014
Received in revised form 8 October 2014
Accepted 24 October 2014
Available online 11 November 2014

Keywords:
Liquid crystals display
Nanoimprint lithography
Blue phase
Polymer
Electrofluidic

ABSTRACT

Modern liquid crystal displays (LCDs) require novel technologies, such as new alignment methods to eliminate alignment layers, fast response and long operation time. To this end, we report an overview of recent efforts in LCD technologies devoted to realize more display modes having no alignment layer, faster switching time and low battery consumption. In particular, we overview recent advances on the liquid crystals (LCs) alignment for display applications, which includes superfine nanostructures, polymeric microchannels and polymer stabilized LCs. Furthermore, we analyze the main optical and electro-optical properties of new generation LCDs displays addressing a particular attention to LCs blue phase hosting gold nanoparticles. Moreover, we focus on the progress of electrofluidic displays, which demonstrates characteristics that are similar to LCDs, with attention on various pixel designs, operation principles and possible future trends of the technology.

1. Advances in liquid crystal alignment for displays

Liquid crystal displays (LCDs) have become important and indispensable in our everyday life due to their compact size, low power consumption and high-resolution density. The portability and compactness of LCDs have initiated and driven new applications and markets such as notebooks, smartphones and large display video cameras [1–4]. All the achievements obtained in the LCDs field have been possible thanks to the decades of extensive research in liquid crystals (LCs) materials. Such extensive research has spearheaded a number of scientific and technical advances with day-to-day applications. LCs are a key component of the displays used in most laptop computers and the increasingly-popular flat panel televisions. Controlled by a network of transistors, LCs change their optical characteristics in response to electrical signals to create the text and images we see. Manufacture of the panels is complex, requiring multiple steps that can introduce defects. Among the steps is the application of a polymer film (e.g. rubbed polyimide (PI)) the so-called alignment layer to the two pieces of conductive glass between which the LCs operate. The film, which must be rubbed after being coated on the glass, anchors the LCs with a fixed alignment. The process of rubbing to create the necessary alignment can damage some of the transistors and introduce dust, producing defects that can reduce the manufacturing yield of the panels. To overcome these issues, various LC alignment techniques have been investigated as alternatives for the PI rubbing approach. Photo-alignment [5–7], ion beam bombardment [8,9], and oblique evaporation of silicon oxide (SiOx) film [10,11] are some of the potential approaches of LC alignment; however alignment instability, materials stability, non-smooth alignment, and low anchoring issues require consideration. Despite the availability of above-cited methods, the possibility of realizing a "surfactant free method" to align any kind of LC and self-organizing material is still an argument of ongoing research. In this section, we will focus on the recent advances on the LC alignment based on nanoimprint lithography (NIL) and an optical active polymeric template realized is soft-composite materials.

* Corresponding author at: Department of Physics and Centre of Excellence for the Study of Innovative Functional Materials (CEMIF-CAL), University of Calabria, Arcavacata di Rende 87036, Italy.
E-mail address: luciano.desio@fis.unical.it (L. De Sio).

http://dx.doi.org/10.1016/j.displa.2014.10.006
0141-9382/

1.1. LC alignment by means of NIL technique

Surface grooves with a suitable pitch and depth are effective in aligning LCs [12,13]. NIL can generate these grooves with a stable and precise pitch so as to lead to good LC alignment. Thus, NIL enables us to precisely control the direction of surface anisotropy and the surface anchoring strength through control of the pitch and depth on a mold, which is hardly possible in the conventional rubbing process. Fig. 1a shows a typical nanoimprinting process. A hard mold that contains the designed features is pressed into a polymeric layer on a substrate at a controlled temperature and pressure, thereby creating a thickness contrast in the polymeric material. A thin residual layer of polymeric material is inevitably left underneath the mold protrusions, and serves as a soft buffer layer that prevents damages of the hard mold on the substrate and effectively protects the delicate nanoscale features on the mold surface. After imprinting, the mold patterns are clearly imprinted into the film having the correspondence as the mirror image each other. This imprint process can be repeated across the substrate areas to obtain multiple imprint fields on the substrate. Fig. 1b and c shows top and cross-sectional scanning electron microscopy (SEM) images of an imprinted nanograting in polymethylmethacrylate (PMMA) [14]. The high-throughput, ultrahigh resolution, and low-cost fabrication makes NIL an attractive and widely researched technology for many applications, such as IC semiconductor device, nanophotonics, and displays. Most imprinting processes can be classified in two main categories: themo-printing and flash-printing, which require the imprinted materials be thermo-curable and photo-curable, respectively. NIL can enable periodic 1D, 2D and 3D structures [15–20], hence having the potential to align LCs in different ways. Various choice of imprinting materials will also affect the LC alignment. Poineer exploration work regarding the LC alignment on the imprinted surfaces has been done in the past decade [21–23]. For LC alignment, materials such as PMMA, poly(dimethylsiloxane) (PDMS), polyimide, SU-8 and polyurethane, have been widely tested. Among them, PMMA, one of common materials for the NIL, is used as a resist material because it has favorable thermal–mechanical properties. The low glass transition temperature (T_g): 90–100 °C, which is a favorable condition to avoid the damage of patterns on a mold surface. Depending on the imprinted material properties, both homogenous and homeotropic alignment can be achieved. For examples, Lin and Rogers have reported parallel LC alignment using three different alignment materials based on the same imprinting mold [24]. The three different materials are a photocurable polyurethane formulation (NOA 73, Norland Inc.), a thermally curable epoxy (SU-82, Microchem Corp.) and photocurable acrylate/methacrylate formulation (SK9, Summers Optical Inc.), respectively. All these three materials have excellent alignment capabilities once they are imprinted using a master PDMS mold. The LC alignment on the imprinted surfaces can be examined under the polarized optical microscope (POM). If the POM images show very uniform darkness and brightness, this indicates that the imprinted surface successfully aligns the LC molecules. In Ref. [25], researchers fabricated a vertically aligned cell using the nanopattern alignment layer. The nanopattern directions on both substrates were parallel to each other, and the cell gap was about 5 μm. Fig. 2 shows the POM view of the sample under the off and on states of the LC cell. In the off state, LC molecules remain perpendicular to the nanopattern surface and the light transmission is prohibited, resulting in a dark image (Fig. 2a). When an external electrical field is applied to the cell (on state), LC molecules shift to a horizontal position, parallel to the NP surface, and the NP LC cell clearly transmits visible light generated from backlight units, resulting in a white image (Fig. 2b). This indicates that uniform alignment was achieved for the NP LC cell. Investigation of the electro-optical properties is a direct way to examine the potential of a nanoimprint technique for LCD applications. Using the imprinted pattern as the alignment layer, a LC cell working in different modes can be assembled and assessed in terms of various parameters (threshold, response times, contrast, etc.) that indicate the performance of display devices. For example, Takahashi et al. have successfully demonstrated homogenous LC alignment using 50 nm ultrafine line and space nanogratings [26]. A twisted nematic (TN) LC cell using the nanogratings as alignment layers showed excellent electro-optical characteristics, as shown in Fig. 3. The measured contrast ratio of the TN cell was 44:1. NIL presents great opportunities for LC alignment. Despite their advantages over the conventional rubbing method, current NIL and platforms are in the infancy stage and require further improvements in various aspects for practical applications. In particular, it is still very challenging to achieve large-area and uniform imprinted pattern for LC

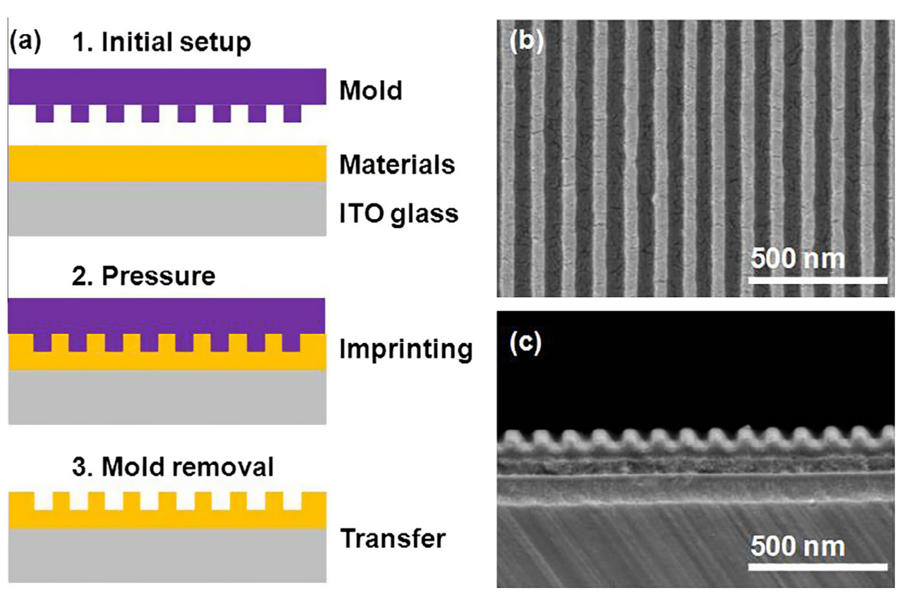

Fig. 1. Typical nanoimprinting process (a); SEM images of top (b) and cross-sectional (c) views of an imprinted nanograting. Figure (b) and (c) is adapted from Ref. [14].