論文の内容の要旨

論文題目　**Large Area MEMS Flexible Color Pixel Sheet by Roll-to-Roll Printing Technology**
（ロール・ツー・ロール印刷技術による大面積ＭＥＭＳフレキシブルカラーピクセルシート）

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This work dealt with the large area micro electro mechanical (MEMS) made by a roll-to-roll printing system. A Fabry-Perot color interferometer device was introduced into this MEMS as a demonstrator. The roll-to-roll process system was firstly set up to support the manufacturing of the designed MEMS on a large flexible substrate. Optical, electrical, and mechanical characterization were applied on this demonstrator to evaluate the MEMS design as well as the roll-to-roll printing process capabilities later on. The successful demonstration proved that both the large area flexible MEMS was realizable and the printing process was applicable. This work then built significant impacts in the MEMS design and application together in the low-cost mass production fields.

1. Introduction

Electronic paper display devices realized by eletrophoretic, eletrochromic, electrowetting, and electromechanic have been published or even commercialized. However, all these devices are with limited display areas and were fabricated by conventional high-cost, low-throughput, and small-batch photolithography process. Furthermore, all these devices suffer from monochrome or impure colors. Thus, to design and develop a suitable manufacturing system for low-cost, high-throughput, and large-area production is highly expected for electronic devices. On the other hand, even though printed electronic products are only with single or double layers, they show promising capabilities especially for flexible substrates.

Flexible Display System: Some academic and commercial ideas were reviewed, evaluated, and compared. All these systems are using liquid material to achieve both flexibility and color variety thus all of these systems suffer reliability concerns.

MEMS Controlled Display System: Micro electro mechanical system (MEMS) display is a well developed technology with commercialization. Four different control types were introduced to set up the basic of this study. The main drawback of MEMS lies on the rigidity.

Printing System: Conventional printing techniques were evaluated to replace current photolithography not only for efficiency but also to support flexible substrates. Good candidates were defined in this section.

Study Goal and Target Application: The main target application is large area flexible decoration with attraction. Four main goals were set up as evaluation references. An example of targeted market was also given here.

Thesis Structure: The over all structure of this thesis was not only graphically illustrated but also explained in detail.

By taking advantages of photolithography processed displays and printing system processed electronics, this study focuses both on the development of novel printing techniques and large area full color flexible display. The goal of this study is to setup a multiple printing-step roll-to-roll manufacturing system and to realize prototype of large scale flexible display by this system.

2. System Design and Simulation

In chapter 1, some flexible display ideas and control mechanism have been introduced. Within them, the Fabry-Perot was evaluated as the most promising system to be controlled by MEMS. This study then chose the MEMS as the flexible display's control system with Fabry-Perot color interference concept.

In this chapter, a multilayer structure will be firstly introduced to explain the Fabry-Perot interferometer system and its application on color filtering. Some equations and calculations will also be given to verify its characteristics followed by simulations. In the same time, a special discussion on materials' behavior will also be given which strongly influence the color filtering effects. Further simulations with different structure designs which include air channels and thickness of different layers will also be carried out to optimize the whole system.

Model: In order to explain and predict its operation, a MEMS model composed of a cantilever and a flat plate was set up and simulated for movement under applied voltage. This is the first time to introduce this superposition model which expects the MEMS device performance and implies improvement solutions.

Structure: Special design concerns were placed on the spacer (barrier) layer. Not only novel air channel shows promising advantages for operation, but also spacer layer itself implies air evacuation path solutions. Great amount of simulations were done to support the MEMS model with predicted best settings.

Color filtering: Transmissive Fabry-Perot color interference is the basic idea for color filtering. By modifying the interferometer (cavity), designed wavelength (color) can be picked out. Detailed material-oriented designs were focused in this part. The display device's dimensional structure was decided according to color designs. A novel quantitative method to judge the color purity by color purity deviation (*CPD*) was proposed and used. By quantifying the purity value on CIE chromaticity diagram, use understands how the purity was improved from a target and how far the experimental data is from the target.

3. Fabrication

With the successful structure set up and model simulation, this chapter will deal with fabrication details. As introduced in chapter 1, a novel process should be used for the special requirement on not only the structure's flexibility but also on the dot spacer layer design. Several promising solutions were examined in chapter 1 and with the structure set up in chapter 2; material, process, and concerns will be discussed layer by layer in this chapter. The main idea is to reproduce a three dimensional circuit structure. New printing processes which show great possibility to replace conventional photolithography process were discussed in this section. A combination of printing processes in series which becomes a roll-to-roll system was developed with high production speed. During the process, both discrete and continuous roll-to-roll system were used and from the operation point of view, both auto and semi-auto system were used.

Material: Candidate material's characteristics of each layer were discussed in this part. Substrate material was chosen to screen out hazardous ultraviolet (UV) light; the electrode material was chosen for the best color filtering effects; the isolation material was chosen with roll-to-roll printing capability; the spacer material was chosen with both printing and lamination capability.

Electrode Patterning: A lift-off process is modified from photolithography was introduced and developed in this part. Each part of this technique showed high-speed, low-cost, and large-area process capabilities.

Thick Layer Printing: Gravure printing was developed for different layers. Rheology characteristic of gravure printing was evaluated for process optimization. A uniform layer is expected for isolation layer, which is the critical part in color modulation. Good relationship between cylinder cell design and printed structure shapes was also setup.

Lamination: Lamination of two layers is not possible in photolithography process; however, printing process provides capability by using adhesive ink. According to the study done on gravure printing, unmerged ink patterns in spacer layer provide similar function as air channel design. Relative contrast (C_R) in spacer area was defined. With extra doping in spacer ink, high relative contrast was achieved to improve the process efficiency.

Roll-to-Roll System: This part shows the integrity and flexibility of previously mentioned printing processes. Detail process parameters such as speed, resolution, temperature, and pressure of each step were discussed. Gravure cylinder parameters of mesh, width, density, depth, screen angle, and contact angle were analyzed to support the rheology designs.

Characteristics: Electrical (electrostatic movement) and optical results was presented in this subsection.

4. Characterization

An active-matrix driven transmissive MEMS-controlled flexible display array designed in chapter 2 was manufactured by roll-to-roll printing processes mentioned in chapter 3. According to the study made for gravure and flexography printing techniques, lift-off (flexography) was chosen for lower electrode patterning while gravure was chosen for isolation and spacer layer. The whole structure was made partly by continuous and partly by discrete roll-to-roll system described above. An area size of 64×118mm (21×39 array) was achieved and a test area of 3×3 array was cut out from the substrate for characterization.

Optical Performance: With the well design of electrode material, device's transmittance achieved 50% in average. The transmittance peaks of three primary colors also showed balanced intensity. The decision of choosing PEN as substrate helped on cutting unwanted UV lights for this transmissive device.

Structural Performance: Newly designed air channel successfully evacuated air trapped inside a display pixel thus helped the on the operation voltage from over 100V to less than 20V. An optimized result with simulation support indicated the best spacer coverage design of 90%.

The color variations according to the view angles satisfied the purpose and goal of decoration application. The variable colors also enhanced this decoration device's attraction.

Electrical Performance: Not only the operation voltage was reduced, but also a dynamic active matrix array was realized. Both successful individual and multiple pixel control of the demonstrator showed its varieties on pattern programming.

Mechanical Performance: A series test proved that this flexible display device can be operated under bending conditions with radii larger than 54mm.

Yield Performance: A 97% and a 100% lift-off process yield for electrode layer was achieved on the sheet to sheet and within sheet, respectively.

5. Discussion

After review the MEMS display device's electrical, mechanical, and optical behaviors in chapter 4, this chapter will deal with some special considerations. These considerations came with the original design and sometimes worsened along the long term operation or the mass production. However, these considerations do not necessarily happen on all samples under all process or operation conditions. Thus the discussions on these considerations help on verifying some root causes of issues and also help on improving the device into a more complete design. The discussions in this chapter will cover the fundamental, process, and operation topics. Potential issues found during this study such as alignment accuracy, color degradation, surface condition, and true color were raised in this chapter with suggested solution.

Alignment Accuracy: The demonstrator was proved to be rotary shifted by semi-auto lamination process. This apparent misalignment can be minimized by process with long substrate with the same method.

Color Degradation: Demonstration colors first enlarged to a larger extent of the display pixel along with activation time then changed colors with elevated operation voltage before finally burned out. The unevenness of isolation layer was the root cause. A solution for this degradation of using two isolation layers was raised. Another roll-to-roll isolation layer process done with sputter is also believed to be flat and solid to persist under pressure.

Surface Condition: Even though the macro view of printed then cured isolation layer done by gravure printing was uneven, the micro view of gravure printed surface covered the surface roughness variation and degradation generated from each process step in the roll-to-roll system. This behavior relieved many potential reliability and color purity concerns published before.

True Color: This study used single electrode material to simplify the process complexity with averaged acceptable primary colors. A solution for true color simulation suggested different electrode materials for different colors was performed for future refinement.

6. Conclusion

In order to manufacture the large area MEMS controlled flexible display device, several novel printing processes have been developed before the realization of this device. The final chapter of this thesis will conclude the achievements from both process and device sides. Here relist the study goals mentioned at the end of chapter 1: support large scales, support flexibility, support vivid colors, and setup a process line to support this device's manufacturing.

The conclusion will qualify the importance and the achievement of this study and will quantify the improvement of each proposal and a prospection section will propose solutions to perfect this idea in the future.

Process: The most important part in the process is the inauguration of a roll-to-roll system. Within this system, novel ideas of gravure printing, flexography printing, and lift-off technique were realized.

Device: An overall solution for the MEMS flexible display device from design, modeling, simulation, and evaluation were performed in this thesis. Based on the printing process developed before, a demonstrator was successfully evaluated for comprehensive optical, electrical, and mechanical properties.

Prospection: A complete structure composed by three primary colors with different layer materials and layer stack was evaluated. This prospection can serve as a reference for the future studies.